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Acurex Corp., Mountain View, CA

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DESIGN REPORT:
LOW-NO_x BURNERS FOR PACKAGE BOILERS

by

R. A. Brown, H. Dehne, S. Eaton, H. B. Mason, and S. Torbov
Acurex Corporation
Environmental Systems Division
485 Clyde Avenue
P.O. Box 7044
Mountain View, California 94039

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EPA Project Officer: William P. Linak
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

Air and Energy Engineering Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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16. ABSTRACT

The report describes a low-NOx burner design, presented for residual-oil-fired industrial boilers and boilers cofiring conventional fuels and nitrated hazardous wastes. The burner offers lower NOx emission levels for these applications than conventional commercial burners. The burner utilizes two-stage combustion in a deep staging mode in which a precombustor firing substoichiometrically is retrofitted to the front of the boiler. The completion of the combustion in the second stage is achieved through sidefire air ports to be retrofitted to the boiler. The precombustor is a cylindrical shell of 2.1 m internal diameter fabricated of lightweight refractory blocks with a Saffil based coating. This material gives a lightweight, nonregenerative precombustor which can adapt to the start-up, shutdown, and load following transients typical of industrial boilers. The precombustor is designed for the capacity range of 15-29 MW heat input. A modular design using annular spool sections adapts to different design loads within this range. For larger loads, a geometric scale-up is required. Design data are also given for 59 MW capacity.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Pollution	Pollution Control	13B
Fuel Oil	Stationary Sources	21D
Combustion Control	Combustion Modification	21B
Nitrogen Oxides	Low-NOx Burners	07B
Boilers		13A

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ABSTRACT

A low-NO_x burner design is presented for residual oil-fired industrial boilers and boilers cofiring conventional fuels and nitrated hazardous wastes. The burner is intended for higher NO_x emission reductions for these applications than conventional commercial burners. The burner utilizes two stage combustion in a deep staging mode in which a precombustor firing substoichiometrically is retrofitted to the front of the boiler. This firing configuration promotes chemical decomposition of fuel nitrogen compounds in the hot, fuel-rich first stage precombustor. The completion of the combustion in the second stage is achieved through sidefire air ports to be retrofitted to the boiler. For the prototype design, stage air can also be injected axially or radially at the throat section between the precombustor and boiler.

The precombustor is a cylindrical shell of 2.1 m (7 ft) internal diameter fabricated of lightweight refractory blocks with a Saffil™ based coating. This material gives a lightweight, nonregenerative precombustor which can adapt to the start-up, shutdown, and load following transients typical of industrial boilers.

Precombustor designs are described for the capacity range of 15 to 59 MW (50 to 200 MMBtu/hr) heat input. A modular design using annular spool sections adapts to different design loads in the range of 15 to 29 MW (50 to 100 MMBtu/hr). For larger loads, a geometric scale-up is required. The burner used with the precombustor is a conventional register burner. Separate atomizer guns are provided for residual oil and nitrated waste firing. The burner also has gas firing capability. The control system maintains precombustor stoichiometry at the conditions for optimum NO_x reduction and the temperature limits of the refractory. Light-off is done at fuel-lean conditions by bypassing stage air to the precombustor until stable temperatures are reached. During normal staged operation, load following is done by proportional controlling of fuel, primary air, and stage air. Waste fuel firing is controlled consistent with the proposed boiler cofiring regulations whenever the boiler load exceeds 25 percent of capacity and waste firing contributes less than 50 percent of total heat input.

This report presents the burner design and sub-scale refractory endurance tests. No field evaluations have been performed.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

The development of the low-NO_x burner design reported here was motivated by two separate regulatory needs for more effective NO_x emission reduction. The first need addressed by the burner is for additional emission control for industrial boilers firing high nitrogen residual oil. This requirement is based on the intent of the Clean Air Act (CAA) to periodically introduce successively lower emission control standards for new sources as part of Section 111 of the Act.

The initial set of new source performance standards (NSPS) for industrial boilers was proposed on June 19, 1984 and revised and promulgated on November 25, 1986.[1] The NO_x standard for residual oil-fired package boilers (heat release rate greater than 730,000 J/s m^3 (70,000 Btu/hr ft^3)) was set at 170 ng/J expressed as NO_2 (0.40 lb/MMBtu as NO_2). This emission level is equivalent to about 310 ppm corrected to 3 percent oxygen. This level is 30 percent higher than the earlier NSPS set for residual oil-fired utility boilers of 129 ng/J (0.3 lb/MMBtu as NO_2). The NO_x standard for industrial boilers with lower heat release (less than 730,000 J/s m^3 (70,000 Btu/hr ft^3)) is the same as the earlier utility boiler standard.

The reason for the higher NO_x emission standard for industrial package boilers was that there was a lack of demonstrated technology which could effectively reduce industrial boiler emissions for the compact package boiler design, without introducing operational problems. Conventional technologies such as commercial low-NO_x burners and sidefire air generally increase flame length. For package boilers, this can lead to tubewall flame impingement since the firebox dimensions are tight to permit boiler shipment by rail or barge.

The 1970 and 1977 CAA Amendments require EPA to periodically review the NSPS and revise the emission standards based on technology developments since the prior review. To support this type of review for residual oil fired industrial boilers, EPA's Office of Air Quality Planning and Standards (OAQPS) identified the need for a combustion modification technology capable of achieving improvement on the current technology for residual oil fired industrial boilers. Although there was no precise emission level which must be achieved, an emission target level of 100 to 125 ppm was suggested by OAQPS for the burner development.

The second regulatory need addressed by the burner development arises from the intent of the Resource Conservation and Recovery Act (RCRA) to promote hazardous waste disposal alternatives to landfill. For liquid combustible wastes, thermal destruction by either cofiring with conventional fuels in boilers or by direct incineration can be an efficient disposal alternative while recovering energy from the waste.

A potential conflict between the CAA and RCRA can arise for those RCRA Appendix VIII compounds and waste categories which contain nitrogen. There are 30 category F and K listings and 114 Appendix VIII compounds, including nitriles, amines, nitrobenzene, and cyanides, which contain bound nitrogen. These wastes may contain nitrogen levels of 10 percent or more. Thermal destruction without extensive NO_x control can increase NO_x emissions by several hundred parts per million relative to conventional fuels. Uncontrolled emissions may reach 1,000 ppm (Figure 1).

The control of NO_x from nitrated waste thermal destruction is complicated by the simultaneous need for low-NO_x and high thermal destruction. For conventional combustion, these are generally opposed conditions. The combustion environment which favors high thermal destruction is high temperature, intense mixing, and long residence time in the hot zone. This environment, however, also favors NO_x formation in conventional combustion. Conventional approaches to NO_x control can, therefore, be counterproductive for thermal destruction performance. The need addressed by the burner development was to control NO_x formation from nitrated waste thermal destruction while not degrading, and possibly improving, waste destruction efficiency.

No firm emission control goal was set since the regulatory need was to avoid high emission increases with cofiring rather than to achieve any specific compliance level. Qualitatively, the goal was to fire wastes with nitrogen levels as high as 10 percent and experience emissions comparable to or lower than conventional combustion when firing residual oil under uncontrolled conditions.

1.2 DESIGN OBJECTIVES

The objective of this project was to design an industrial boiler low-NO_x burner for firing residual oil or cofiring nitrated waste. The quantitative design objectives are listed below. In addition to the quantitative goals are several qualitative goals relating to the impact of the burner on boiler operation. These goals are motivated by the potential constraining effects of modified low-NO_x conditions on boiler operational flexibility. The performance goals used for the burner design were:

- Fuels: high nitrogen residual oil
    - Nitrated waste cofired with residual oil
    - Natural gas and distillate oil for light-off and backup
- NO_x emissions: 100 to 125 ppm with residual oil
    - 200 to 300 ppm with nitrated waste cofiring
- Carbon monoxide: <35 ppm
- Smoke emissions: <4 Bacharach number
- Capacity: 15 to 59 MW (50 to 200 MMBtu/hr) thermal input
- Boiler application: retrofit or new source application for major design types (D, A, and O) of single burner boilers
- Turndown: >5:1
- Destruction efficiency with waste firing: >99.99 percent
- Operational flexibility: startup, shutdown, and load following transients comparable to conventional burners
- Size: minimal constraint on retrofit space requirements
- Burner controls: integrated to existing boiler controls in retrofit application
- User oriented

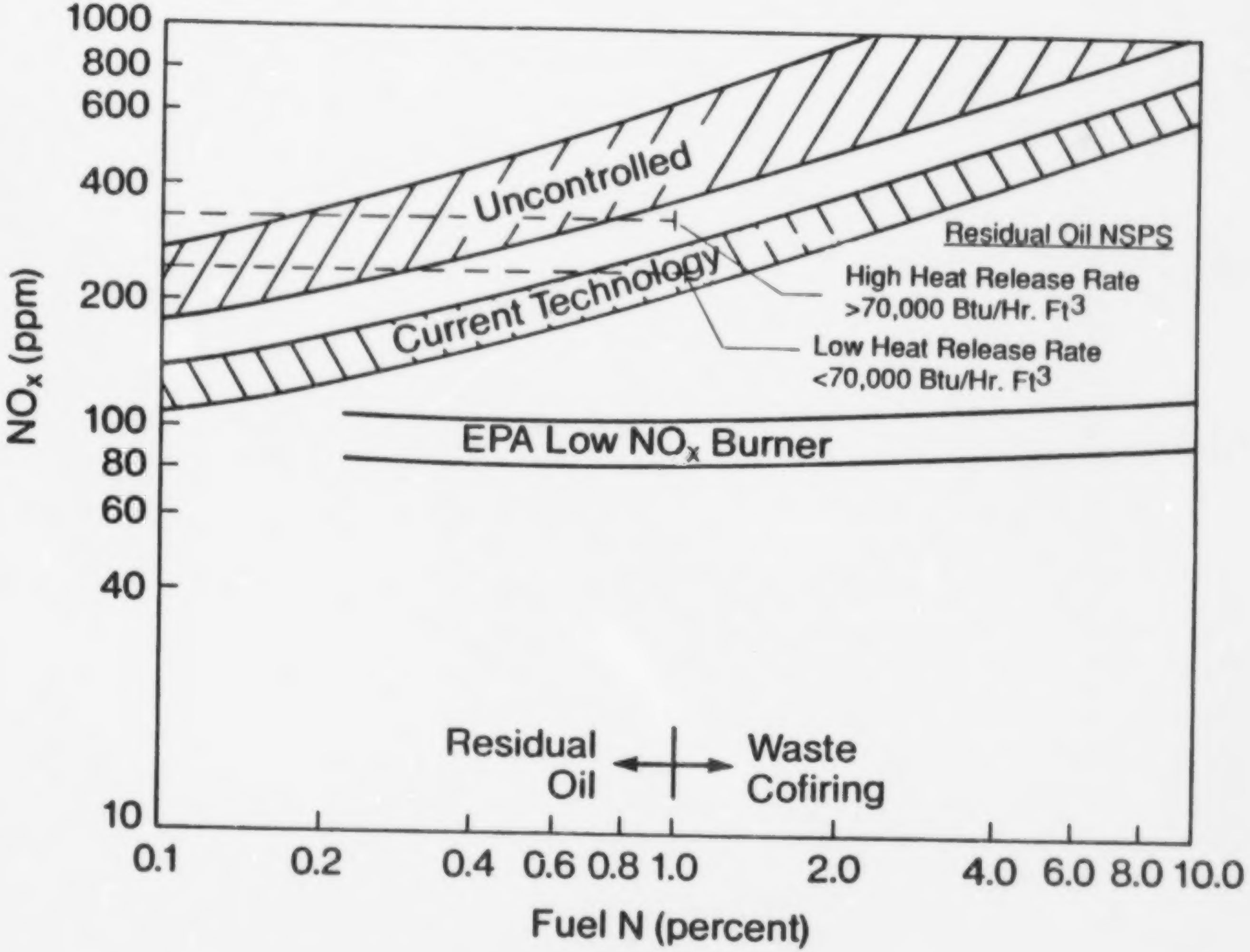


Figure 1. Oil-fired NO_x controls.

The stated design objectives for burner heat input capacity are very broad. At the start of the program, the design objective was focused on the upper end of the range of package boiler heat input capacities: 59 MW to 74 MW (200 to 250 MMBtu/hr). This range was chosen because the package boilers in the upper end of the capacity range exhibited the highest volumetric heat release and hence the higher potential for operational problems with modified low NO_x combustion. This capacity range was regarded as the greatest challenge to achieving low NO_x emissions with acceptable operational impacts.

Early in the project, the design objective for capacity was lowered after initial boiler user surveys showed there were few operators in the high end of the capacity range using residual oil. The capacity design range was lowered to 37 MW (125 MMBtu/hr) to include a significant number of boilers firing residual oil and still retain the emission reduction challenge inherent in the original objective.

Further along in the project, the design objective for capacity was further lowered to 15 MW (50 MMBtu/hr) after surveys of nitrated waste generators showed that the lower capacity boilers were used more frequently for nitrated waste cofiring than the larger package boilers. The composite range of 15 to 59 MW was finally selected to give broad coverage of both high nitrogen residual oil applications as well as cofiring of high nitrogen wastes. Across the entire capacity range, the emphasis in the design was to achieve the performance goals with minimum compromise on boiler operational flexibility.

1.3 APPROACH

At program inception, the intent was to carry the burner development through to the field evaluation of a prototype full scale burner retrofit to an existing boiler firing residual oil, and, as an option, cofiring nitrated waste. Consistent with this field hardware focus, a major initial task in the program was the site survey to find an appropriate site for the field evaluation. Seven months into the program, the funding was truncated to allow only design development and supporting bench scale testing. Accordingly, the site survey effort was terminated and the subsequent effort refocused on the conceptual design evaluations reported in Section 2 and the detailed design development reported in Section 3. For completeness, the progress made in the site selection is summarized in Appendix A. Data from supporting bench scale testing is summarized in Appendix B. Because the funding was truncated, the intended field evaluation was not conducted and the program concluded with the design effort and sub-scale endurance testing reported herein.

The design reported here is for a prototype burner intended for the initial qualification and optimization testing. As such, the design contains more flexibility in air and fuel distribution and control and instrumentation than would be used in an eventual commercial burner. This is particularly necessary in the current project, where it was the intent to proceed directly to a field prototype checkout without pilot scale testing. Thus, testing of the overall burner performance, materials behavior, and optimization of stoichiometry and air distribution would need to be done with the first prototype article. After the initial prototype tests, the operational characteristics of the burner would be known and the design could be simplified for routine application.

SECTION 2

CONCEPTUAL DESIGN

2.1 TECHNICAL OPTIONS

The present industrial boiler low-NO_x burner development is an extension of an earlier sequence of EPA burner development and scale-up projects. This developmental sequence focussed on achieving low levels of NO_x emissions during high-nitrogen oil firing through use of an advanced degree of two-stage combustion.

The fundamental concepts underlying the burner design were developed in the 1970's, and carried through to the hardware stage in the early 1980's in a series of scale-up tests. Sarofim[2] in 1976 conducted fundamental evaluations of the form and fate of fuel nitrogen species in fuel-rich and fuel-lean conditions. He suggested that conversion of fuel nitrogen decomposition products to NO_x could be largely suppressed if the products were held at substoichiometric, high temperature conditions for a sufficient period. For this initial fuel rich first stage, the high temperature accelerates the reduction of nitrogen species to molecular nitrogen and lowers final flue gas NO_x, in contrast to the lean combustion case where high temperature promotes NO_x formation.

The deep staging concept was validated in the subscale by Brown[3,4] for coal firing and England[5] for oil firing. For both fuels, sub-scale results showed a hot, fuel-rich first stage with long exposure time was very effective in suppressing fuel nitrogen conversion. Starting in 1980, EPA supported testing to identify the best combination of first stage temperature, stoichiometry, and residence time to minimize first stage fuel nitrogen intermediaries, and stage air injection configurations to minimize second stage fuel nitrogen conversion and second stage thermal NO_x. A scale-up sequence was performed on combustors with heat input capacities of 20 kW (70,000 Btu/hr), 0.6 MW (2 MMBtu/hr), and 3 MW (10 MMBtu/hr).

The EPA oil burner scale-up sequence culminated in the development of a 16 MW (55 MMBtu/hr) heat input prototype combustor shown in Figure 2[6]. This combustor was built for EPA by EER Corporation. It uses a first stage burner/combustor fabricated from heavy brick refractory and designed for regenerative cooling of the outer shell by incoming combustion air.

The prototype burner/combustor was retrofit to an enhanced oil recovery (EOR) steam generator near Bakersfield, California[7]. The retrofit burner-steamer configuration shown on Figure 3, achieved NO_x emissions as low as 65 ppm when firing local crude oil[8]. The burner thermal response was very slow, but proved adequate to the EOR application which is base loaded for long, sustained operational periods. The thick, hot refractory also presented special considerations for emergency shut down or operation under low load.

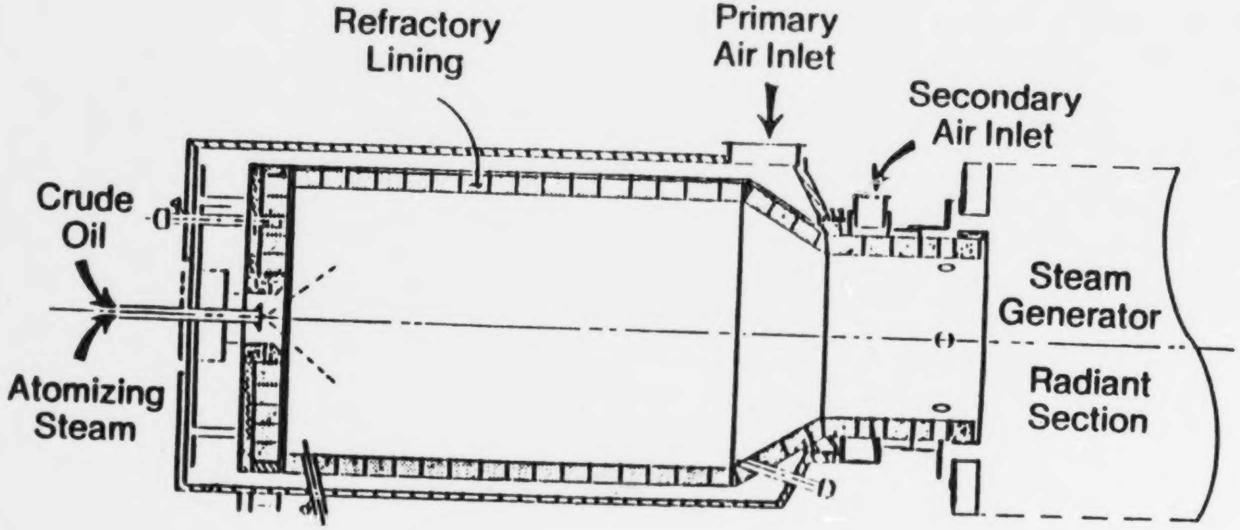

Refractory Lining
Primary Air Inlet
Secondary Air Inlet
Crude Oil
Atomizing Steam
Steam Generator
Radiant Section

Figure 2. Prototype EOR burner.[8]

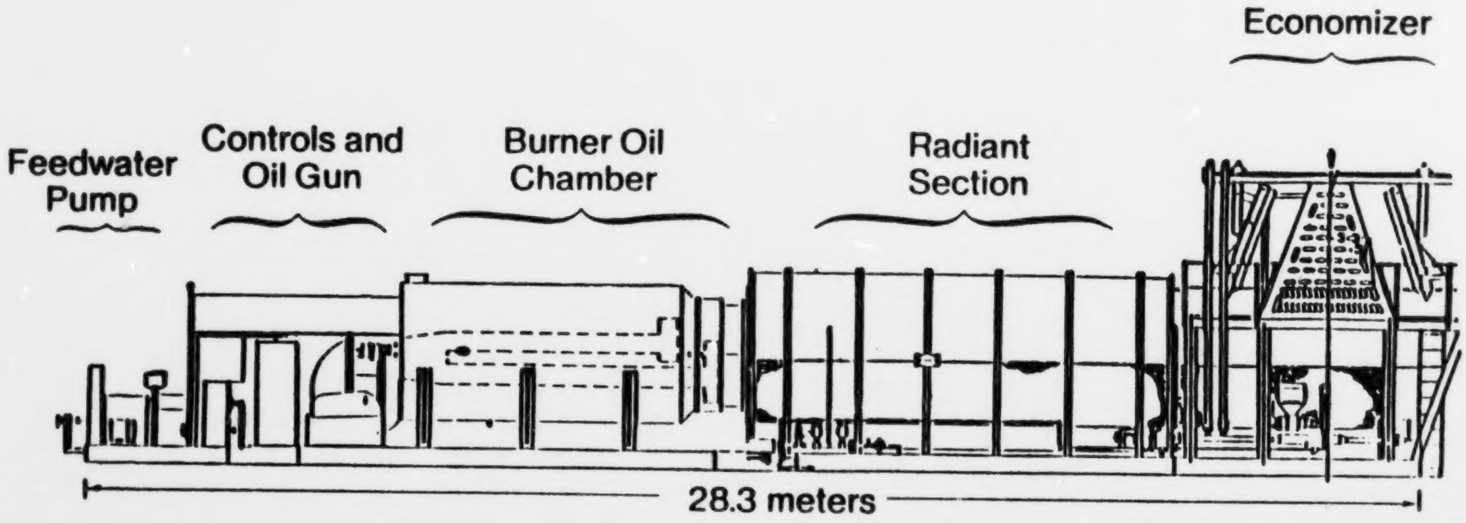

Feedwater Pump
Controls and Oil Gun
Burner Oil Chamber
Radiant Section
Economizer
28.3 meters

Figure 3. EOR low-NO_x burner retrofit.[6]

In July 1984, the EPA low-NO_x burner program was reviewed by an industrial peer review panel preparatory to starting the present industrial boiler project. The panel viewed the 1984 burner development as adequate for the EOR application, but in need of some redirection for the industrial boiler market. Industrial boilers typically require much faster start-up, shut-down, and load following response and higher turndown than EOR steamers. Industrial boilers also have more complex control systems which must be integrated to the burner control logic. Industrial boilers are typically in an industrial plant with stringent safety requirements for combustion equipment. In addition, the package industrial boilers have much higher combustion intensities and tighter fireboxes than EOR steamers, increasing the importance of tailoring the retrofit burner flame shape to the parent boiler.

The peer review panel set the following guidelines for the industrial boiler low-NO_x burner development:

- Improved thermal response for start-up, shut-down, and load following
- Higher turndown
- Size reduction
- Improved safety
- Upgraded control system

In accomplishing these goals, the panel suggested that more advanced refractory materials be considered. The conceptual design of the industrial boiler low-NO_x burner was based on the goal of using as much as possible of the earlier EPA oil burner technology while addressing the peer review panel comments and the design goals listed in Section 1. In addition, it was clear that satisfying the peer review panel comments would require significant changes to the design. Yet, it was desireable to avoid further developmental testing. Accordingly, an additional goal was added that the first full-scale prototype hardware article would be very flexible in design to permit limited developmental testing during the field evaluation.

In satisfying these requirements with the deep staging concept, several technical trade-offs needed to be evaluated to arrive at a practical configuration with commercial potential. The trade-offs are generally grouped as to those affecting the first stage, precombustor section, and those related to the second stage, boiler section. The major trade-offs are as follows:

First Stage

- Total fixed nitrogen (TFN) decay vs. residence time (size)
- TFN decay vs. precombustor temperature
- Precombustor temperature and TFN decay vs. stoichiometry
- Precombustor temperature vs regenerative cooling configurations
- Thermal response and regenerative cooling vs. refractory materials

Second Stage

- NO_x vs. first stage exit temperature
- NO_x vs. temperature at stage air injection
- NO_x vs. stage air mixing patterns
- Carbon and CO burnout vs. second stage residence time
- Flame shaping vs. interstage throat (choke) design
- Turndown performance vs. throat design

The approach taken to the conceptual design was to first focus on refractory selection. This was done first since refractory material affects how most of the other trade-offs can be exercised. The refractory selection also is the most important choice in satisfying the peer review panel comments since material specification affects start-up, shut-down, and load following thermal performance, ultimate turndown achievable, and safety requirements.

For refractory selection, a wide range of regenerable and fully insulated designs using conventional heavy refractory, newer thin heavy refractory materials with thermal shock resistance, and newer lightweight fiber bricks were evaluated. Several emerging refractory materials were attractive but presented too much developmental risk for a commercial burner. The best compromise in achieving high thermal performance with acceptable developmental risk was a fully insulated design using lightweight fiber block bricks. This offers essentially unconstrained thermal transient flexibility within the thermal limits of the material. The primary design concerns with this material are the upper temperature limit of 1570°C (2850°F), the relatively low mechanical strength, and the lack of prior experience in a turbulent, fuel rich burner application.

The selection of the lightweight refractory material satisfies the thermal performance goals of the industrial boiler application. The goal of reduced size was approached in two ways. First, the NO_x emission goal was critically reviewed, and the trade-offs identified. The prior EOR work showed that very low NO_x levels on the order of 65 ppm could be achieved, but only at the price of a large, unwieldy combustor. There are major size reduction benefits in going to a higher NO_x target, as quantified in the subsequent pages.

This issue of size vs. NO_x target was discussed with EPA's Office of Air Quality Planning and Standards who had initially requested the present program. OAQPS requested the project to improve on the commercial low NO_x burner capability available when the industrial boiler NSPS was written. When the NSPS was promulgated in December, 1987, the NO_x emission control limit with high nitrogen residual oil firing in a package boiler was on the order of 330 ppm. Developments since 1987 have not radically changed that situation for package boilers, although much lower levels can be achieved in field erected units. The tight firebox in package boilers severely constrains commercial NO_x control techniques. In that context, OAQPS viewed an emission target for the new burner of 100 to 125 ppm as a logical goal. Reductions below that range would probably not be used on a nationwide basis for many years, although it could be needed selectively in some districts.

A similar situation exists for the alternate burner use for nitrated waste cofiring. The demand for a low NO_x burner for this application was primarily to prevent NO_x emissions from exceeding typical emissions from conventional fuels rather than to seek stringent reductions below conventional. Therefore, for both residual and waste fuels a size reduction in the burner could be tolerated without compromising the intended market for the burner. The NO_x emission goal with residual oil was accordingly raised to 100 to 125 ppm.

The second approach to size reduction is to use sidefire air for second stage air injection rather than injecting stage air at the throat as was done with the EOR steamer. This gives some useful residence time in the boiler for TFN decay which would normally need to be added to the precombustor volume. The delayed staging also allows prior cooling of the first stage products which will reduce second stage thermal NO_x. The benefits from this approach are ultimately limited by freezing of the fixed nitrogen kinetics which gives no further NO_x reduction from increased residence time, and by increasing CO and soot emissions if insufficient second stage residence time is allowed.

The goal of designing high flexibility into the initial prototype article was approached in several ways. The overall combustor shell is designed from modular spools to allow changes in residence time in the field. Stage air is ducted so it can be added through sidefire ports on the boiler as well as either axially or radially at the throat. The burner control system is also more flexible to accommodate parametric variation of fuel and air flows.

Satisfying the remaining design goals and settling on a configuration requires evaluating tradeoffs in residence time, temperature, stoichiometry, and positioning of stage air ports. These tradeoffs are summarized in the following section.

2.2 CONFIGURATION TRADEOFFS

2.2.1 Performance Data and Calculations

Extensive combustor configuration testing was done on the earlier EPA enhanced oil recovery steamer burner development project and on an in-house EPA project.[8,9] This testing explored the effects of parametric variations of residence time, temperature, first stage fuel air mixing, and stage air mixing on overall NO_x emissions and on interstage total fixed nitrogen concentrations. Accordingly, no additional configurational testing was done for the current boiler design since the primary conceptual changes are to use an insulated rather than regenerable design and to use lightweight rather than heavy brick refractory. These changes should still allow use of much of the previous test data, although considerable interpolation and extrapolation is needed to apply to the specific design configuration selected here. An additional change in the industrial boiler application is to use side fire air rather than throat injection of second stage air. This staging configuration was not generally covered in the previous EPA testing and engineering estimates are necessary to quantify NO_x emission trade offs for this addition to the design.

This section summarizes the key test data interpretations and design calculations leading to the selection of the conceptual design configuration.

The overall concept of the deep staging EPA low-NO_x burner is to promote decay of fuel nitrogen intermediary species by the use of high temperatures in a substoichiometric environment. Figure 4 shows kinetic calculations for simulated fuel oil flame using methane with one percent fuel nitrogen.[7] This shows the trade offs of NO_x with higher temperature and residence time. In the present design, the temperature ceiling is effectively set by refractory material limits. The residence time benefits are traded-off against excessive space requirements and increased costs with larger combustor sizes. The curves show the diminishing returns in NO_x reduction in going to residence times much over 300 msec. This is due to the slowing of the reactions when the TFN concentrations are increasingly reduced.

In the current design, part of the boiler space will be used for TFN decay by introducing stage air from side-fire air ports in the boiler rather than at the throat between the precombustor and boiler. This will effectively increase the residence time for TFN decay without increasing the size of the precombustor.

The use of sidefire boiler ports for injecting second stage air is also effective for reducing second stage NO_x created during the completion of combustion of the carryover fuel from the first stage. By cooling the first stage gases prior to staging, the temperature rise is held to a level limited only by the need to leave sufficient downstream space for carbon burnout.

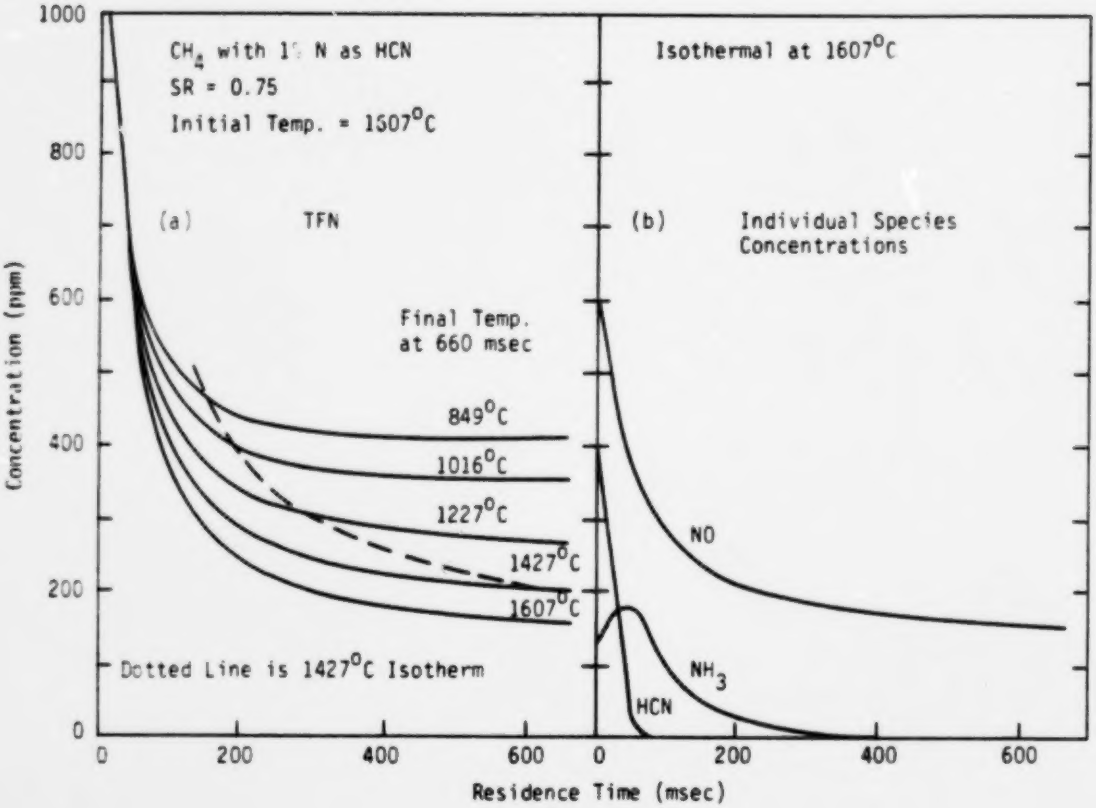


Figure 4. Chemical kinetics for TFN and NO for simulated fuel CH_4 with 1% N as HCN.[7]

The quantified tradeoffs on NO_x, temperature and residence time are illustrated by test data interpolations from the prior EPA test program shown on Figure 5. The data on the left panel of the figure show the TFN concentrations at the end of the first stage for various residence times and chamber temperatures. The correlation of NO_x from conversion of TFN is shown on the right panel. Also shown is the indicated conditions for the design point selected for the industrial boiler precombustor low-NO_x burner. At that condition, the contribution to total NO_x from the first stage is 112 ppm.

Design calculations for combustor and boiler thermal conditions and for space requirements for second stage air injection were made for a typical California crude oil. The oil used for design calculations had the following ultimate analysis, in percent:

Water	0.4
Sulfur	1.13
Ash	0.08
Nitrogen	0.78
Carbon	85.67
Hydrogen	11.18
Oxygen	0.76
Total	100
LHV	9855 kCal/kg (17,738 Btu/lb)

The equilibrium flue gas combustion products for various stoichiometric ratios are shown on Figure 6. The corresponding adiabatic flame temperature and a predicted temperature accounting for heat loss are shown on Figure 7 for the fuel. The heat loss calculation accounted for heat conduction through the combustor shell as well as radiative losses through the precombustor throat into the boiler waterwalls. The corresponding data are listed on Table 1.

The effect of stage air injection on firebox temperatures was modeled with a boiler heat transfer calculational algorithm. A 15 MW (50 MMBtu/hr) heat input capacity boiler was used for the calculations. Typical design data for an O-type package boiler configuration was used for the heat exchange surface orientation in the model. Figure 8 shows the predicted temperatures and residence times for staged combustion with side-fire air. Zone I is the region of the boiler where decay of TFN species from the first stage continues, although at a low rate. Zone II is the second stage where combustion is completed and second stage thermal NO_x is generated. T_1 is the temperature at the exit of the precombustor, T_2 is the temperature at the stage air port location, and T_3 is the exit temperature of the firebox. The location of the stage air ports was selected as 2.13 m (7 feet) from the front wall. This is the approximate distance where the TFN decay kinetics are frozen and no further fuel nitrogen reduction accrues from downstream placement of the ports.

The results of the temperature analysis show the residence time with sidefire staging is longer than without sidefire air and the temperatures are lower. This is a result of the lower velocities and higher cooling in Zone I when staging is used compared to single stage combustion.

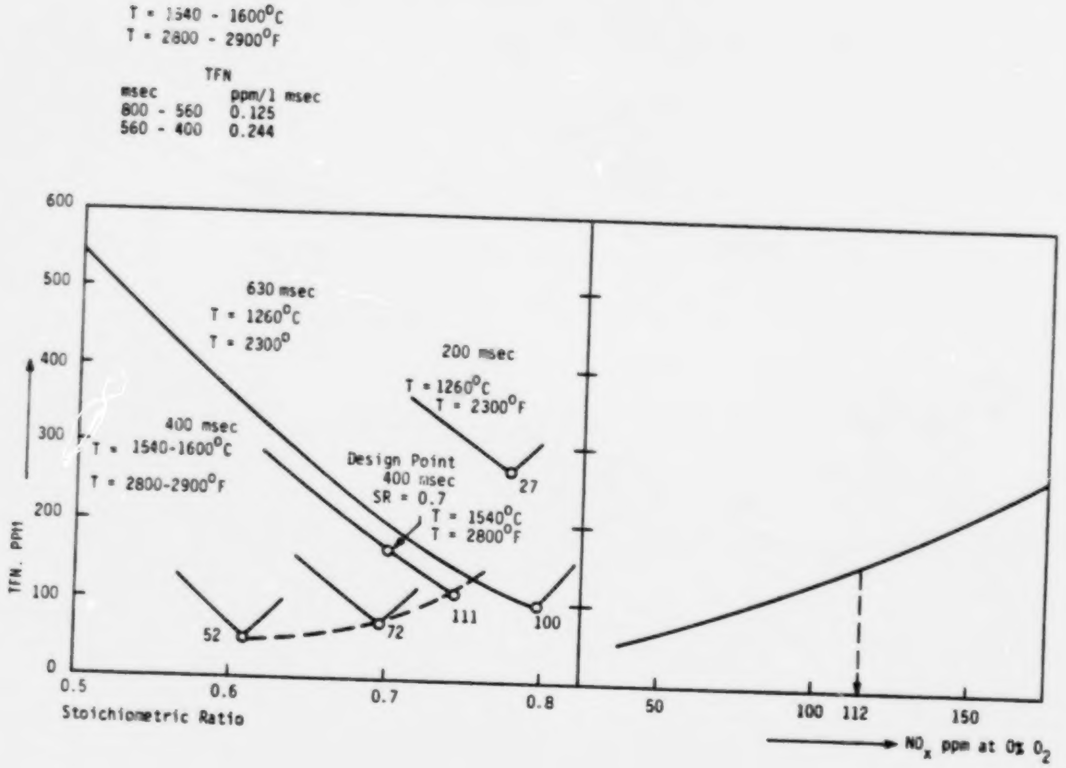


Figure 5. TFN data for different combustors.

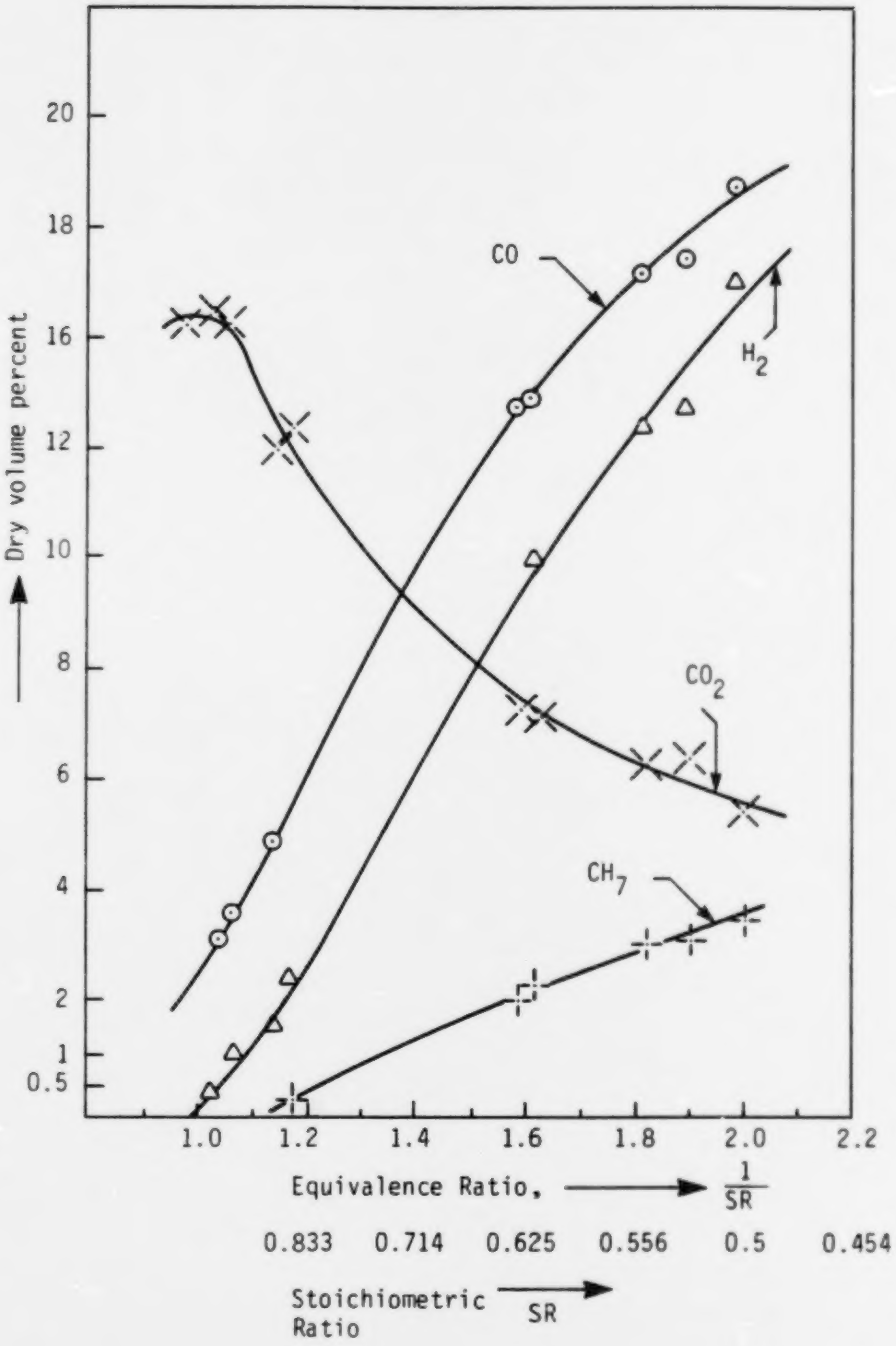


Figure 6. Flue gas analysis for different stoichiometries.

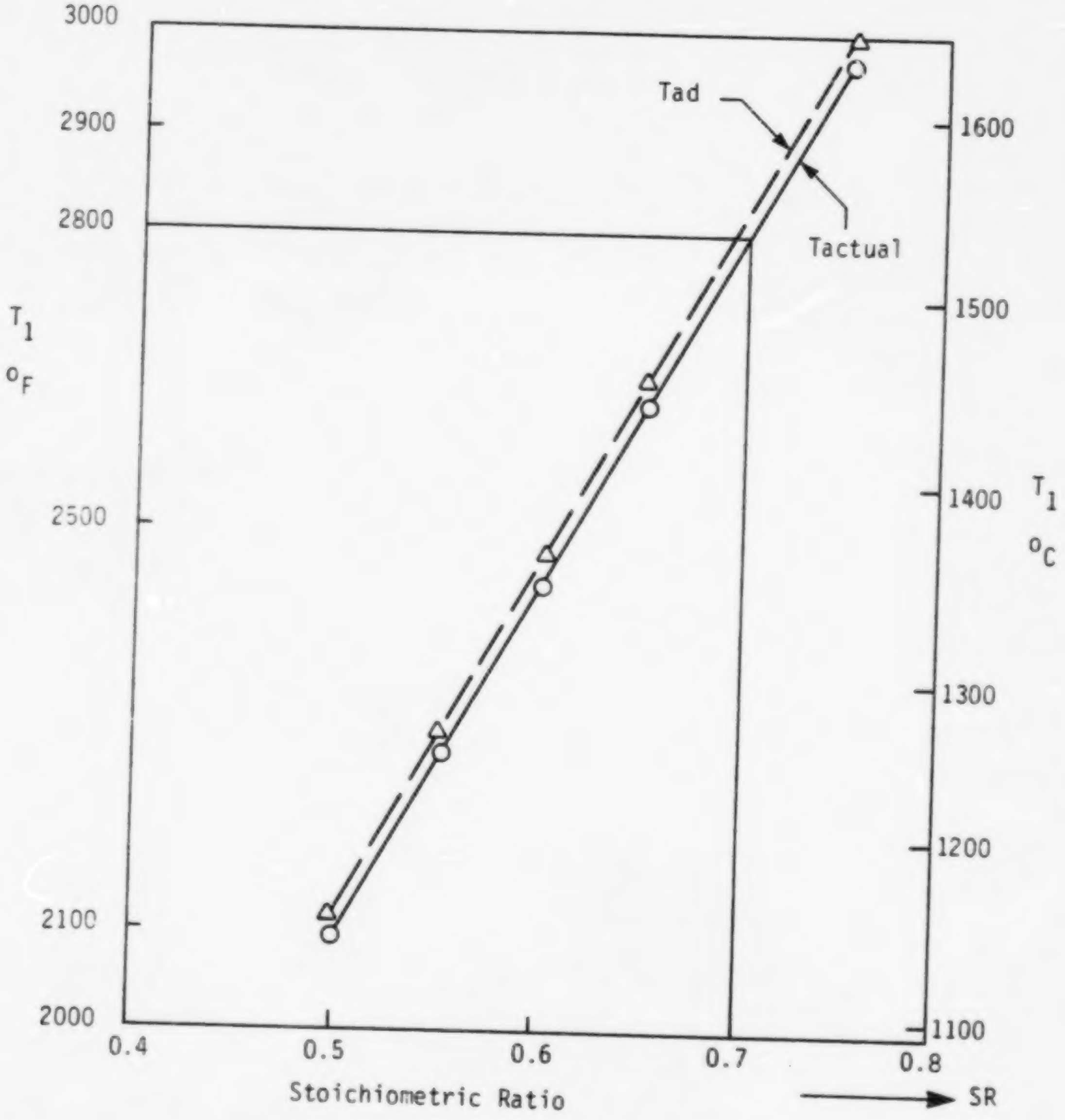
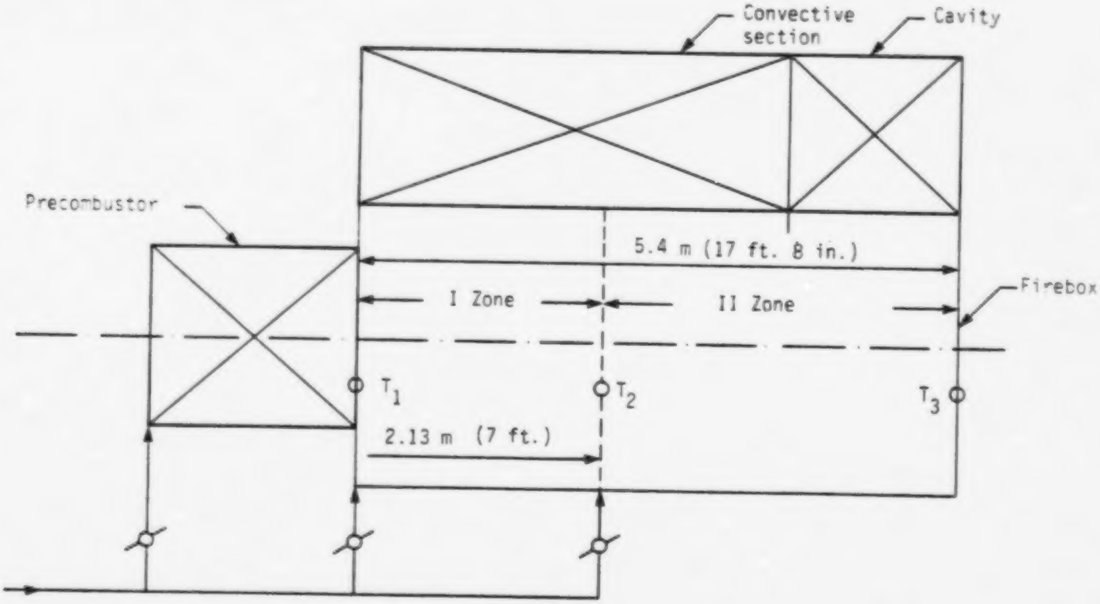


Figure 7. Combustor temperatures.

TABLE 1. ADIABATIC AND PREDICTED FLAME TEMPERATURE

SR	Fuel Input kcal/kg	Air Input (25°C) kcal/kg	Tad		T_{real}	
			°C	°F	°C	°F
0.50	1927	42.0	1157	2115	1146	2095
0.55	5420	46.2	1261	2302	1247	2277
0.60	5912	50.4	1362	2484	1346	2455
0.65	6405	54.7	1464	2667	1442	2628
0.75	7391	63.1	1665	3029	1635	2975


Convective section
Cavity
Precombustor
5.4 m (17 ft. 8 in.)
Firebox
I Zone
II Zone
T_1
T_2
T_3
2.13 m (7 ft.)

With Air Staging

Parameter	T_1	T_2	T_3	Resid Time (msec)
Zone I	1540°C (2800°F)	1020°C (1870°F)		680
Zone II		1380°C (2510°F)	1000°C (1830°F)	620

Without Air Staging

Parameter	T_1 °F	T_3 °F	Resid. Time (msec)
Firebox	1540°C (2800°F)	1080°C (1970°F)	900

Figure 8. Air staging temperature profiles: 15 MW (50 MBtu/hr) boiler.

The NO_x performance for the industrial boiler application was predicted using the thermal model described above, together with kinetic calculations, and empirical correlations from the prior EPA low-NO_x burner program.[6] Figures 9 and 10 show predicted fuel nitrogen and NO_x environments for a 15 MW (50 MMBtu/hr) boiler with the precombustor in a deep staging mode. These results show the 112 ppm TFN from the first stage as also shown on Figure 5. The additional residence time in Zone I of the boiler is sufficient to reduce the TFN by 27 ppm to a level of 85 ppm before the TFN kinetics are frozen. The conversion in stage II of this TFN carryover, combined with a 25 ppm second stage thermal NO_x increment, estimated from the temperature at staging, leads to a predicted NO_x level of 85 ppm (at 3 percent O_2). This is a conservative approach to the design goal of 100 to 125 ppm. If the lower levels are readily attainable in the prototype demonstration, removable modules, or spools, in the combustor shell can be taken out to reduce the residence time (and combustor size) as a tradeoff to higher NO_x.

The deep staging configuration must allow sufficient residence time in the second stage for carbon particulate and carbon monoxide burnout. A semiempirical carbon burnout calculation was made to estimate the time-temperature conditions for sufficient burnout. These results were compared with the time-temperature distributions resulting from the thermal modeling discussed above for a 15 MW (50 MMBtu/hr) package boiler.

Experimental data from residual oil gasification is used to estimate the solids burden from the first stage for a stoichiometric ratio of 0.75.[10] The data on Figures 11 and 12 show a solids burden of 3.25 percent for air atomization and 1.75 to 2.5 percent for steam atomization. These levels should be augmented by the ash content of the oil, which is 0.08 percent for the typical oil used in the design calculations. For these conditions, the initial soot concentration ranges from 560 to 730 ng/J (1.3 to 1.7 lb/MBtu). For a target emission level, the utility boiler New Source Performance Standard is 43 ng/J (0.1 lb/MBtu). For a visibility level of less than 5 Bacharach, the corresponding concentration is about 0.2 g/Nm^3 (Figure 13) which corresponds to a carbon burnout from the first stage exit of 80 to 90 percent.

A semiempirical soot burnout kinetic calculation was made for 1 micron particle diameters which research has shown to be the most prevalent size fraction for oil soot. These calculations showed that a residence time of about 230 msec is required to bring the initial soot loading down to the target levels. Since a residence time of 620 msec is available for the selected design point, sufficient space is allowed for burnout. The safety factor in residence time will give margin to cover the case of larger particles and compensate for possible agglomeration.

Carbon monoxide burnout was also estimated from a semi-empirical kinetic expression. The CO at the exit of the precombustor is 10.4 percent as taken from the equilibrium calculations from Figure 6. For the thermal conditions used in the design calculations, the CO burnout time is 1 msec. This indicates, as expected, that soot burnout is the critical factor.

Even though the design calculations indicate burnout should not be a problem with sidefire air, the prototype design will include provision for stage air injection also at the transition throat section from the precombustor to the boiler. This will give added flexibility in the event combustible emission problems occur.

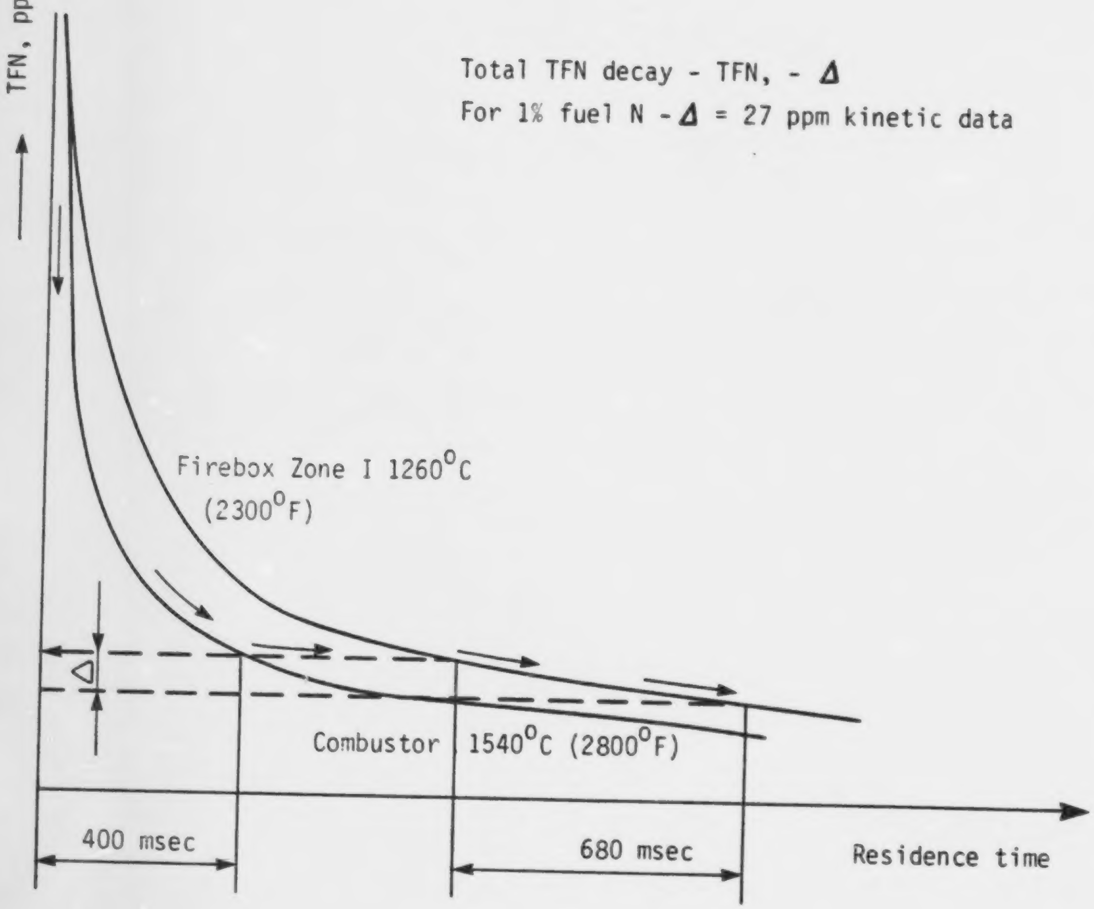

TFN, ppm
Total TFN decay - TFN, - Δ
For 1% fuel N - Δ = 27 ppm kinetic data
Firebox Zone I 1260°C
(2300°F)
Δ
Combustor
1540°C (2800°F)
400 msec
680 msec
Residence time

Figure 9. Combustor-boiler firebox TFN decay process.

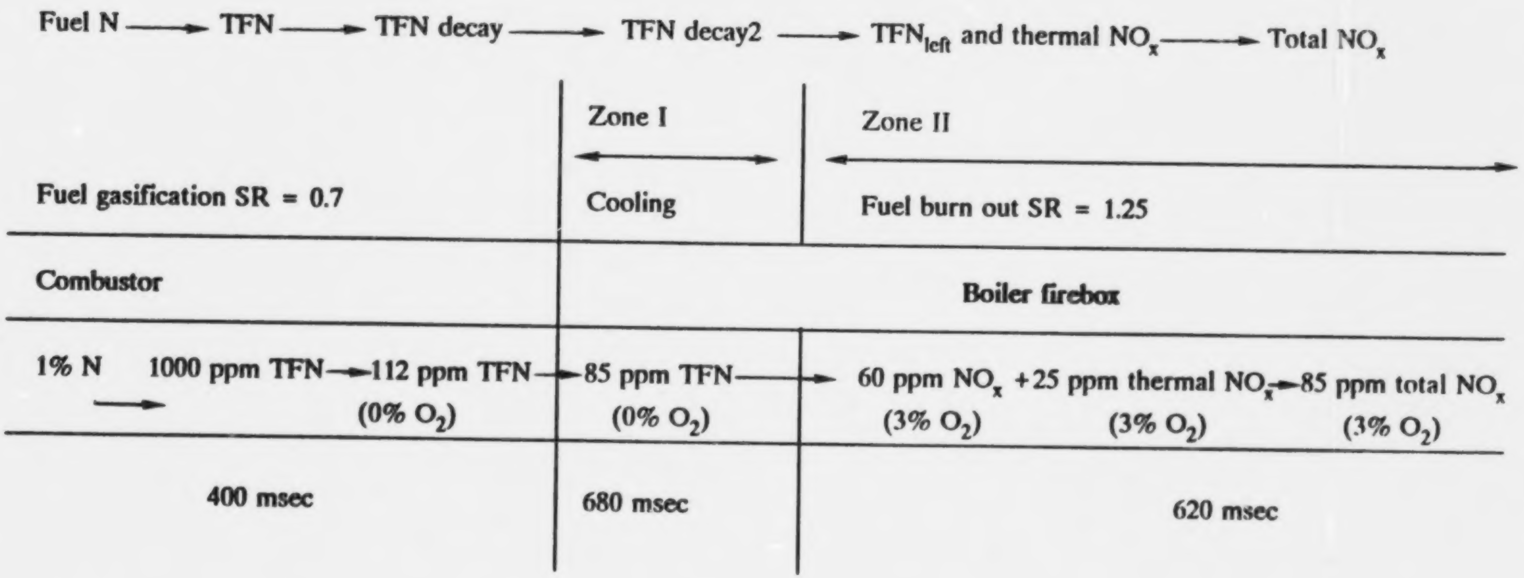

Fuel N → TFN → TFN decay → TFN decay2 → TFN_{left} and thermal NO_x → Total NO_x
Zone I
Zone II
Fuel gasification SR = 0.7
Cooling
Fuel burn out SR = 1.25
Combustor
Boiler firebox
1% N → 1000 ppm TFN → 112 ppm TFN (0% O_2) → 85 ppm TFN (0% O_2) → 60 ppm NO_x (3% O_2) +25 ppm thermal NO_x (3% O_2) → 85 ppm total NO_x (3% O_2)
400 msec
680 msec
620 msec

Figure 10. NO_x formation and prediction.

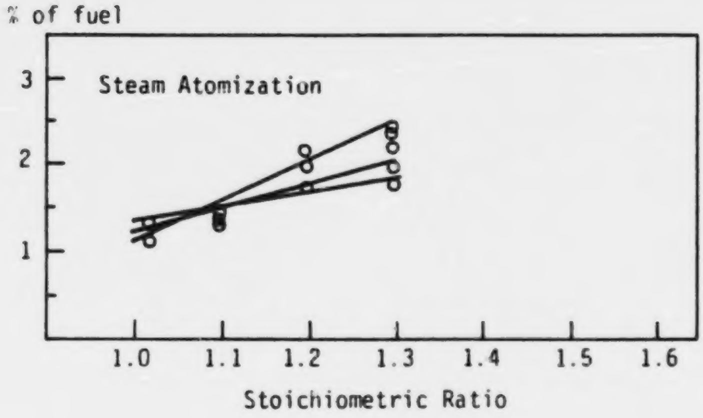


Figure 11. **Solid burden from gasifier with steam atomization.[10] (Courtesy of the Journal of the Institute of Energy [formerly the Journal of the Institute of Fuel])**

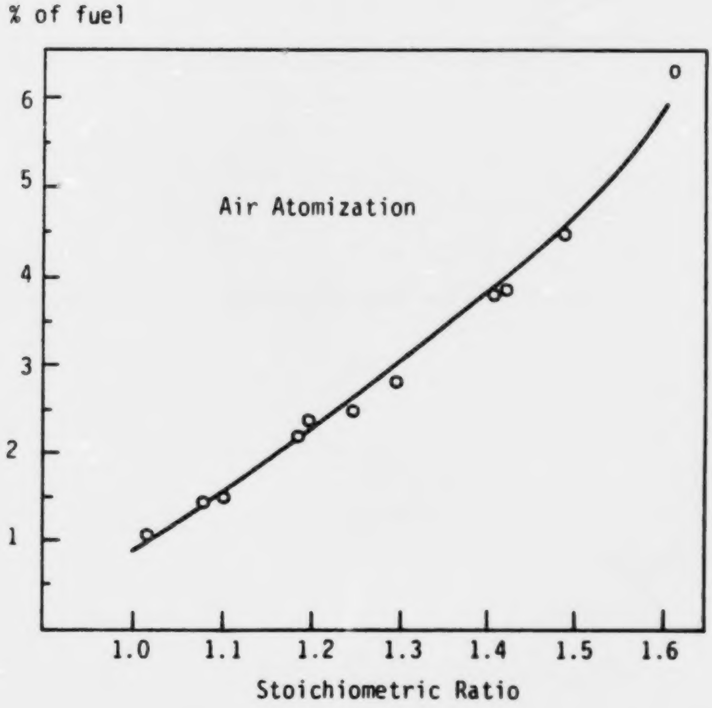


Figure 12. **Solid burden from gasifier with air atomization.[10] (Courtesy of the Journal of the Institute of Energy [formerly the Journal of the Institute of Fuel])**

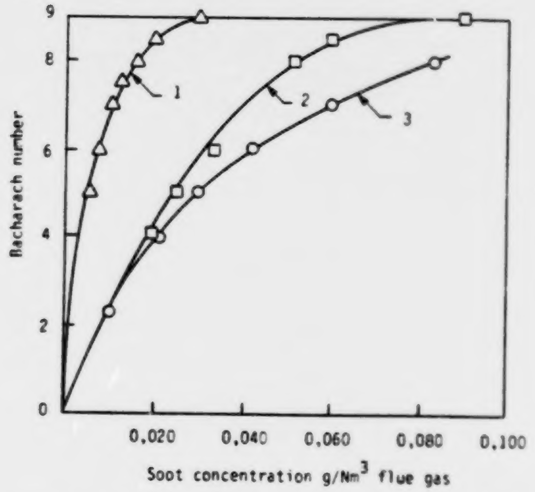


Figure 13. Bacharach soot concentration g/Nm^3 flue gas.

2.2.2 Configuration Selection: 15 MW (50 MMBtu/hr) Thermal Input

The capacity range of the primary prototype design is 15 to 29 MW (50 to 100 MMBtu/hr). Secondary design data are also given for the original program focus in the 59 MW (200 MMBtu/hr) capacity range. The lower heat input capacity range was selected for the primary design because the increasingly important application to waste thermal destruction was far more likely to occur with the smaller equipment. Boiler surveys indicated that most waste generators had boilers in the smaller capacity range, and it was relatively rare to find a boiler as large as 59 MW (200 MMBtu/hr) at the waste generation site.

The lightweight refractory nonregenerable fully insulated precombustor shell design was selected as discussed in Sections 2.1 and 2.3. Some design calculations were also made for the emerging advanced concept of a thin refractory coating over a metal shell in a regenerable design. Although this material is too risky for current use, it shows potential for effective application upon further development. The design concept using this material is discussed in Section 2.4.

The precombustor stoichiometric ratio was taken as 0.7 based on the NO_x formation analysis and the temperature limits of 1540°C (2800°F) for the lightweight fiber refractory (Figure 7). The residence time for the precombustor is taken as 450 msec to allow time for oil droplet evaporation and pyrolysis and the nitrogen decay events predicted from the formation analysis (Figure 10).

The internal diameter of the precombustor is taken as 2.1 m (7 ft) based on the typical size of the front wall of 15 MW (50 MMBtu/hr) boilers. This diameter is also based on an analysis of the droplet trajectory in the atomized fuel jet to avoid wall impingement with the lightweight refractory. The 2.1-m (7-ft) diameter should ensure that droplets evaporate before impinging on the wall surface.

This internal diameter, together with the 450 msec residence time dictates an internal combustor length of 2.7 m (9 ft). The precombustor will be fabricated in modules, or spools, so that residence time can be varied in the prototype, and a similar design can be used for different capacity boilers. The 29 MW (100 MMBtu/hr) capacity precombustor can be fabricated by adding an additional spool module to the 15 MW (50 MMBtu/hr) design.

The throat diameter at the transition from the precombustor to the boiler is determined from the requirement that exit velocities are below 35 m/s (115 ft/s) to retain similar combustion gas aerodynamics in the firebox. The exit velocities for a standard burner design is 30.5 to 43 m/s 100 to 140 ft/s. The resulting throat diameter is 0.9 m (2.9 feet) for the 15 MW (50 MMBtu/hr) design, and 1.2 m (4 ft) for the 29 MW (100 MMBtu/hr) capacity.

2.2.3 Configuration Selection: 59 MW (200 MMBtu/hr)

The 59 MW (200 MMBtu/hr) heat input combustor design and process parameters are similar to the 15 MW (50 MMBtu/hr) design. The total residence time of combustion gases in the primary combustor remains at 450 msec and the temperature after combustion and gasification of the oil is 1540 to 1556°C (2800 to 2850°F), which corresponds to the same NO_x emission design estimate of 85 ppm which was used in the primary prototype design.

The internal diameter of the chamber for the larger capacity is increased from 2.1 m (7 ft) to 2.7 m (9 ft) for two reasons. One reason is to avoid flame impingement to the cylindrical wall with larger flame sizes. The second is to reduce the total combustor length. This configuration is compatible with the dimensions of a package boiler of 59 MW (200 MMBtu/hr) capacity. The internal length, 5.8 m (19 ft), corresponds to a total combustion length of 7.6 m (25 ft). For industrial boiler applications, this will require special considerations of access in front of the boiler and will pose some difficulties for retrofit of existing units.

The exit throat diameter is 1.5 m (5 ft) which corresponds to an exit velocity of 34 m/s (115 ft/sec). That degree of choke essentially keeps the boiler firebox flow pattern the same as with the original burner. It also avoids flame impingement on the heat exchanger water walls and does not reduce the flue gas residence time in the secondary firebox.

2.3 REFRACTORY CONCEPT FOR THE FULLY INSULATED DESIGN

The insulated lightweight refractory concept was chosen to permit the flexible duty cycle required in an industrial boiler application. Specifically, the lightweight refractory will allow the rapid start-up, shut-down, and load changes in package boiler applications without destructive thermal shock as could be the case with castable or brick refractories. The material has been used extensively in heat treating furnaces and drying ovens. There is some developmental risk in applying this material to the precombustor internals with the highly turbulent aerodynamics and contact with fuel rich species including reduced sulfur compounds. Accordingly, durability endurance tests were done for a spool section of a sub-scale precombustor fired on residual oil and gas. These results are summarized in Appendix B.

For the fully insulated precombustor design, different refractory materials are used for the cylindrical body, for the front section with the burner throat, and the rear section with the transition throat. The cylindrical section is fabricated with the full fiber refractory in modules installed directly to the metal surface. The full modules are designated "Pyro-Bloc® Plus" modules. Figure 14 illustrates the overall refractory mounting configuration. This refractory configuration poses virtually no constraints on boiler load changes or startup transients.

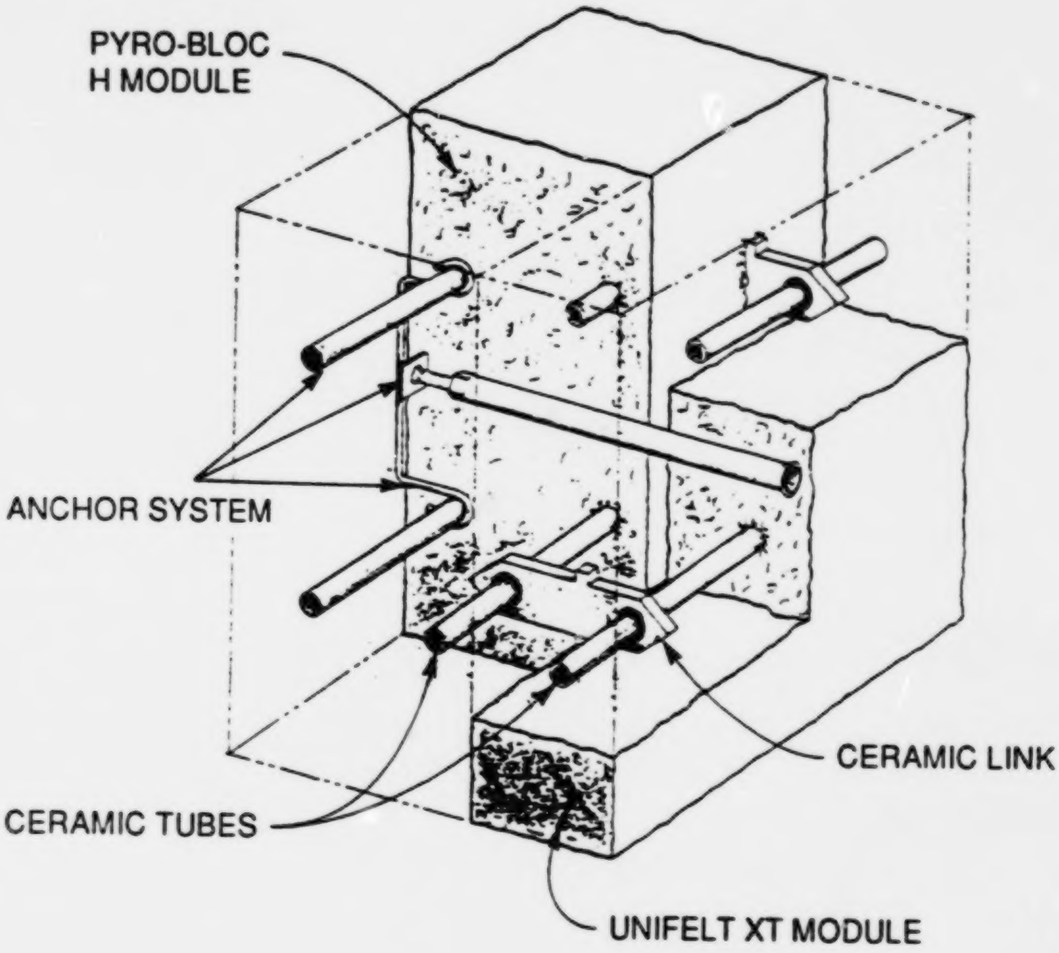

PYRO-BLOC
H MODULE
ANCHOR SYSTEM
CERAMIC LINK
CERAMIC TUBES
UNIFELT XT MODULE

Figure 14. Pyro-Bloc Plus module.

Figure 15 shows the assembley and relative dimensions of the three layer refractory for the cylindrical section. The components and thermal properties of the refractory sections are as follows.

Section I is Pyro-Bloc H. It has a maximum design limit use of 1340°C (2450°F), a recommended long term use temperature limit of 1320°C (2400°F), and a standard density of 192 kg/m^3 (12 lb/ft^3). The thermal conductivity of the Pyro-Bloc H is as follows:

12# Pyro-Bloc H

	Temperature Range		Thermal Conductivity (Btu.in/hr. ft^{2}F)	Thermal Conductivity (J/m.hr.C)
	°F	°C		
1.	200	94	.4280	222
2.	400	205	.4938	256
3.	600	316	.5910	307
4.	800	427	.7160	371
5.	1000	538	.8665	450
6.	1200	649	1.0414	540
7.	1400	760	1.2392	643
8.	1600	871	1.4578	756
9.	1800	982	1.6934	879
10.	2000	1094	1.9393	1006
11.	2200	1205	2.1856	1134
12.	2400	1316	2.4179	1254

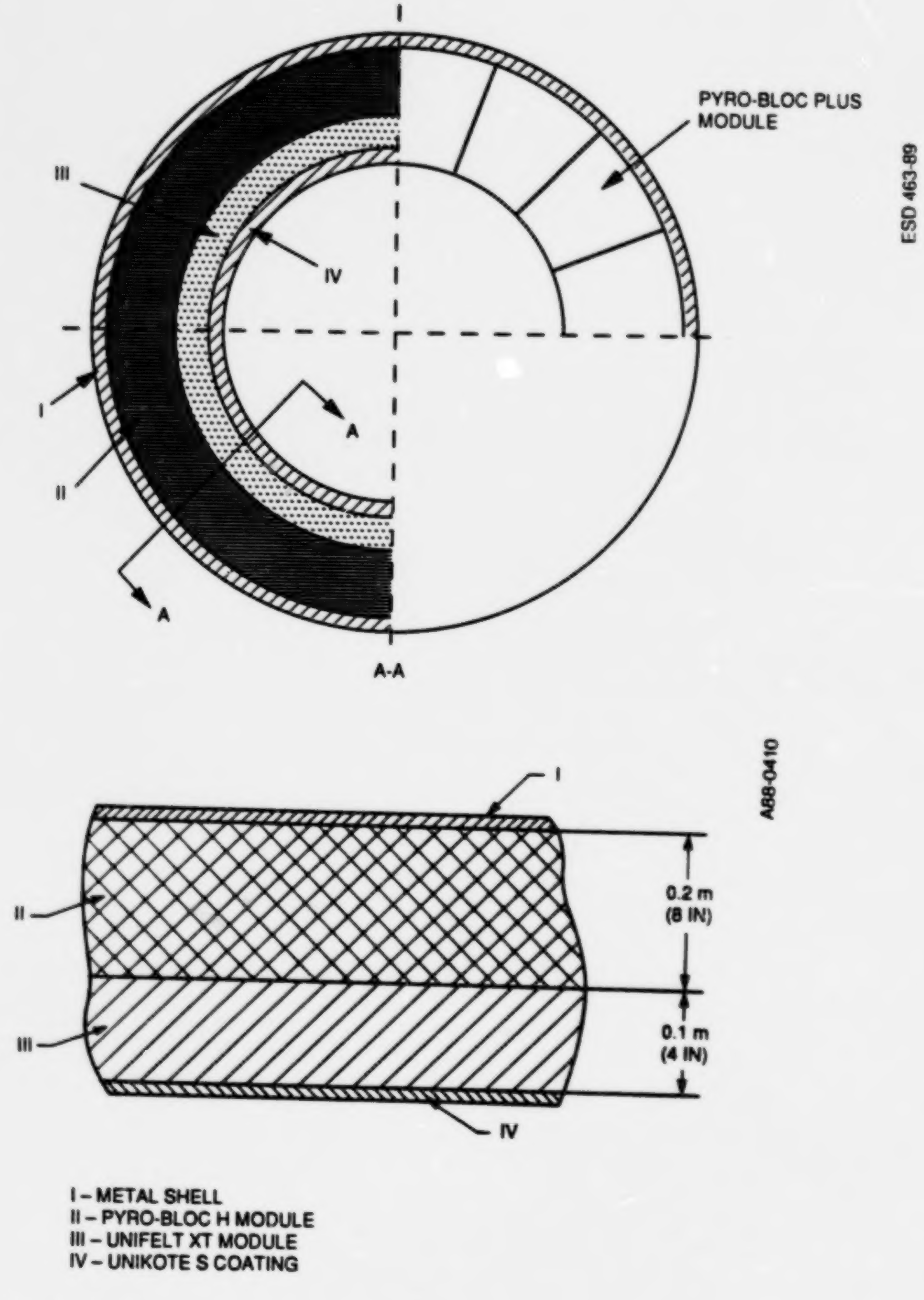

PYRO-BLOC PLUS MODULE
ESD 463-89
III
IV
I
II
A
A
A-A
A88-0410
I
II
III
IV
0.2 m (8 IN)
0.1 m (4 IN)
I – METAL SHELL
II – PYRO-BLOC H MODULE
III – UNIFELT XT MODULE
IV – UNIKOTE S COATING

Figure 15. Combustor cross section, Pyro-Bloc Plus module arrangement.

Section II is Unifelt® XT module with a maximum design temperature of 1650°C (3000°F), a recommended long term temperature limit of 1570°C (2850°F), and a standard density of 141 kg/m^3 (9 lb/ft^3). The thermal conductivity of the Unifelt XT is as follows:

Unifelt XT

	Temperature Range		Thermal Conductivity (Btu.in/hr. ft^2°F)	Thermal Conductivity (J/m.hr.K)
	°F	°C		
1.	200	94	.7226	375
2.	400	205	.7540	391
3.	600	316	.8098	420
4.	800	427	.8825	458
5.	1000	538	.9720	504
6.	1200	649	1.0834	562
7.	1400	760	1.2247	635
8.	1600	871	1.4045	729
9.	1800	982	1.6300	846
10.	2000	1094	1.9048	988
11.	2200	1205	2.2267	1155
12.	2400	1316	2.5852	1341
13.	2600	1427	2.9597	1535
14.	2800	1538	3.3173	1721
15.	3000	1649	3.6103	1873

Section III is Unikote™ S with a use limit of 1650°C (3000°F), and a melting point of 1879°C (3400°F).

Pyro-Bloc H is a dimensionally stable non-hygroscopic alumina silica fiber. It is formed in standard blocks with a square cross section 0.3 m (1 ft) on a side and with thickness selected for the application. Each block is attached to the cylindrical surface of the combustor with the anchoring system. The anchors consist of stainless steel tubes, stainless steel brackets and nut and bolt fasteners. The nut is welded to the cylindrical shell surface with a special tool during the installation.

The Unifelt XT module is a Saffil™, high alumina, high purity thermally stable fiber. Saffil fibers provide improved performance over ceramic fibers because of their microcrystalline structure and ultra-high alumina content (over 95 percent).

The Unifelt XT veneer is attached to the Pyro-Bloc H module with ceramic links and ceramic tubes through each module. The Unikote S coating is spayed over the module surface after the installation. The coating serves as an initial protection of the module surface during the start up and thermal curing of the fiber module refractory. After the fiber is cured and solidified, any subsequent partial loss of the coating is not critical for refractory lifetime. The coating can be periodically reapplied as a part of a regular maintenance schedule. The physical properties of the Unikote S coating materials are:

Unikote S

Appearance	White	kg required per m^2	3-4
Type	Dry powder	Lbs required per ft^2, 1/16" to 1/8" thick	0.6-0.8
Specific gravity	1.11	Installation method	Spray
Use limit, °C (°F)	1650 (3000)	Mixing water, %	40-50
Melting point, °C (°F)	1870 (3000)	**Chemical Analysis (%)**	
Linear shrinkage, % after firing		Alumina (Al_2O_3)	88
@ 1300°C	0.3	Silica (SiO_2)	12
@ 1400°C		Other	--
@ 1480°C	0.5		

Figure 16 shows the nomenclature for the heat transfer analysis through the cylindrical wall which was done to confirm that temperatures are within design limits. The radiative component of the heat transfer at the inner wall is:

$$Q_r,_{fl} = 4.9 \times 10^{-8} \times \epsilon^1_w \times \epsilon_{fl} \times (T^4_{fl} - T^4_1)$$

The convective heat transfer at the inner wall is:

$$Q_c,^{fl} = \alpha_c x (T_{fl} - T_1).$$

Here,

$$\epsilon_w^1 = \frac{1 + \epsilon_w}{2} = 0.9 \text{ effective wall emissivity}$$

ϵ_w = Wall emissivity = 0.8

ϵ_{fl} = flame emissivity = 0.57

T_{fl} = flame temperature, K

T_1, T_2, T_3: Wall temperature, K

α_c = Convective heat transfer coefficient
= 13.6 k cal/m x h x C

The heat transfer through the wall is driven by the free convection heat transfer around the outer wall:

$$\frac{T_3 - T_a}{\frac{1}{\alpha_a}} = \frac{T_2 - T_3}{\frac{\delta 1}{k_1}} = \frac{T_1 - T_2}{\frac{\delta 2}{k_2}} = Q_{fl,r} + Q_{fl,c}$$

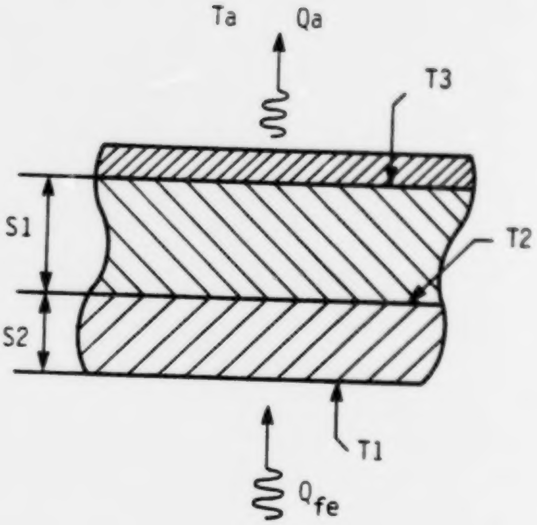


Figure 16. Heat transfer through the cylindrical wall.

An iterative solution gives for the temperatures,

T_1 = 1540°C (2800°F)

T_2 = 1300°C (2380°F)

T_3 = 93°C (198°F)

Tfl = 1540°C (2802°F)

This analysis confirms that with a flame temperature around 1540°C (2800°F) in the precombustor, the temperatures of the refractory materials in the insulation are below the maximum allowable for continuous operation. The distance between the metal shell and the anchoring system is 4.1 cm (1 5/8 in.). The temperature in that area averages 340°C (643°F). For these conditions, the anchoring system should be made with 309 stainless steel. Also, since the shell temperature is below 100°C (212°F), water vapor from the flue gas could condense on the internal surface of the outer metal shell forming an acidic mixture from the sulfur and nitrogen species in the flue gas. The extent of this effect will be small, since there is no driving force for combustion gases to penetrate through the refractory. In any event, the inner skin of the metal shell should be coated with a teflon coating to suppress acid attack.

The front and rear end plates of the precombustor use a more complex structure to accommodate the burner and combustor throat and the need for greater thermal conduction away from the wall. The front and rear wall designs are shown on Figures 17 and 18, respectively. The burner and combustor throats are fabricated from castable refractory which has sufficient strength to be self supported. The castable will also be anchored by the studs welded to the front plate and to the boiler front wall tubes. A lightweight castable refractory is placed behind the castable plastic refractory in the front plate assembly. This provides thermal insulation, while the castable and the studs conduct heat away from the localized hot spots on the front face. Design calculations as well as tests at a facility not related to this program show that the enhanced thermal conduction is necessary to avoid overtemperature of the cement bonding the outer refractory to the inner surface. The properties of both front wall refractories are listed on Tables 2 and 3.

The internal wall of the precombustor is covered by a Saffil Unifelt XT veneer module to enhance thermal protection and obtain better thermal stress properties. The veneer module is attached to the castable plastic refractory with a high-temperature Unistik™ cement with physical properties as shown in Table 4. The thermal analysis for the front wall similar to the cylindrical analysis discussed above showed the following temperature levels:

- Inner skin temperature: 1540°C (2800°F)
- Interface temperature of the veneer and castable: 1400°C (2550°F)
- Interface temperature of the castable and lightweight refractories: 1335°C (2434°F)
- Outer skin temperature: 72°C (161°F)

These temperature limits confirm that the materials will be within their permissible temperature ranges. This is particularly critical for the cement bond which holds the Saffil veneer lining to the castable. The temperatures in the back wall will be lower since the heat removal from the boiler tubes will reduce temperatures. The thermal analysis was not repeated for the back wall.

The nonregenerable fully insulated design discussed here appears to allow reliable operational temperatures, acceptable outside temperatures which will require only a protective grid, and will permit combustor operation without any limitations on the start up rate and capacity change under transient conditions.

2.4 REFRACTORY CONCEPT FOR THE REGENERABLE DESIGN

The regenerable concept is considered as a potential future application which needs development and demonstration before it can be credibly used for burner fabrication. The technology is under development for gas turbine cans and as a high temperature corrosion protective barrier in numerous applications. The technology employed is to use a zirconium silicate substrate bonded to a single compliant layer of sintered metal fibers. The inner layer compensates for thermal expansion and permits the ceramic to reconfigure to reduce stresses. The fiber metal layer has a modulus of elasticity lower than the ceramic or typical metals used in fabrication. It also has a high elastic limit of approximately 2 percent elongation. The sintered pad is attached to a solid metal base using conventional alloys. The ceramic can be deposited on the fiber pad by direct plasma spraying of a bond coat and ceramic. The low elasticity modulus values of the pad induce low stresses in the ceramic layer and allows the metal shell to move independently of the ceramic layer in a high temperature environment with high temperature gradients.

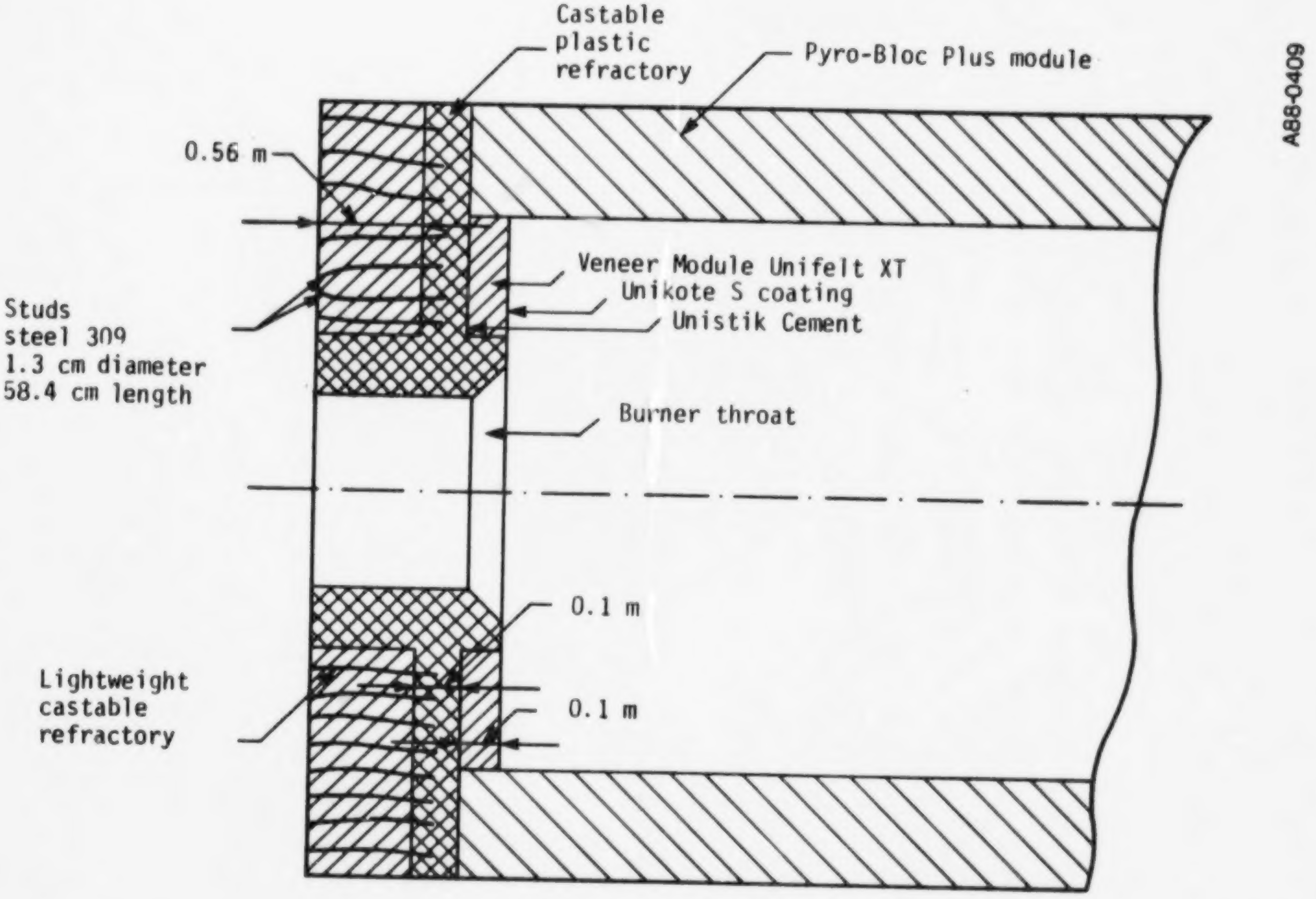

Castable
plastic
refractory
Pyro-Bloc Plus module
A88-0409
0.56 m
Veneer Module Unifelt XT
Unikote S coating
Unistik Cement
Studs
steel 309
1.3 cm diameter
58.4 cm length
Burner throat
0.1 m
Lightweight
castable
refractory
0.1 m

Figure 17. Combustor front end plate and wall assembly.

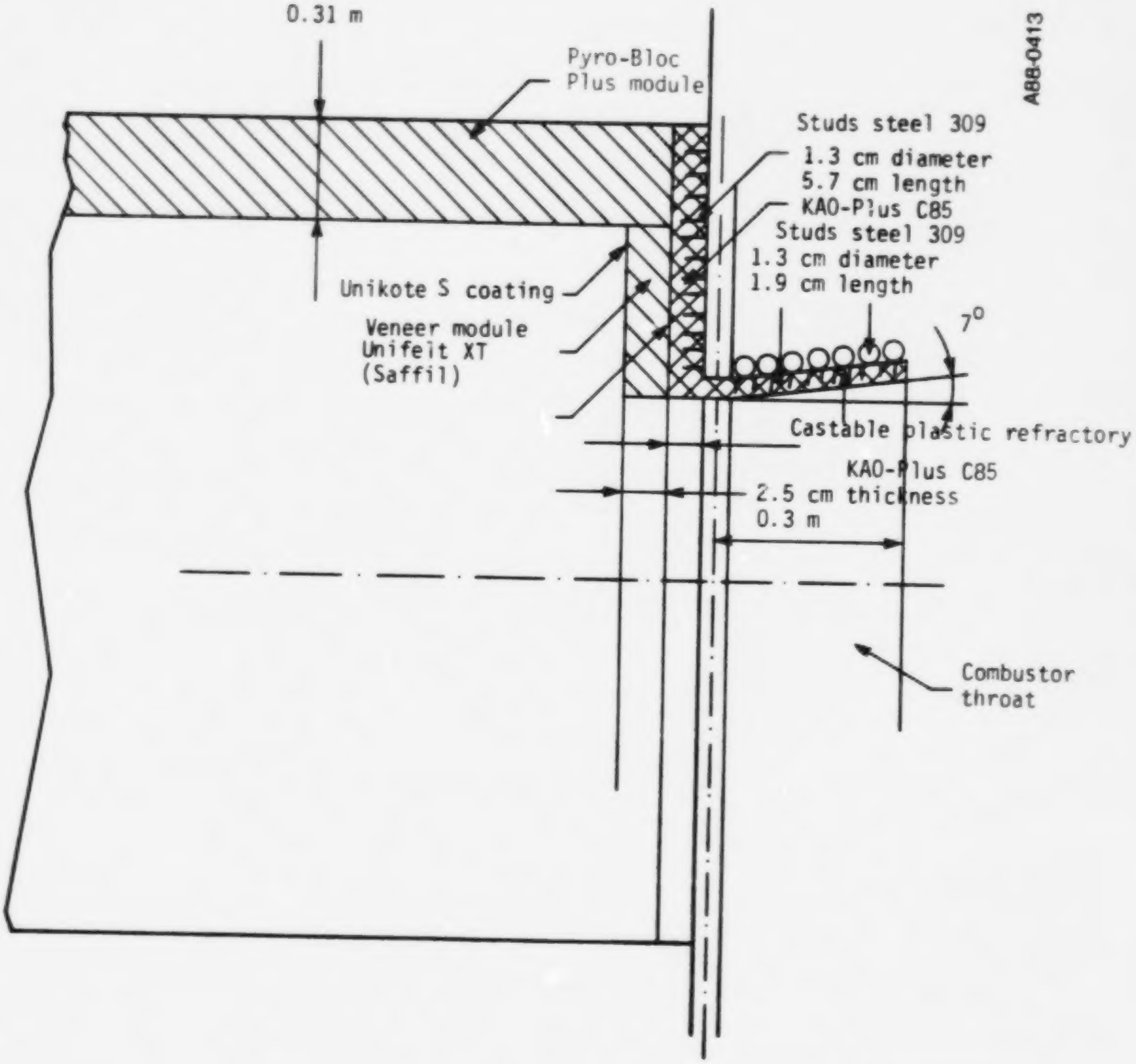

0.31 m
Pyro-Bloc
Plus module
A88-0413
Studs steel 309
1.3 cm diameter
5.7 cm length
KAO-Plus C85
Studs steel 309
1.3 cm diameter
1.9 cm length
Unikote S coating
Veneer module
Unifelt XT
(Saffil)
7°
Castable plastic refractory
KAO-Plus C85
2.5 cm thickness
0.3 m
Combustor
throat

Figure 18. Combustor rear wall throat design.

TABLE 2. KAO-PLUS C85 CASTING PLASTIC MONOLITH-AVERAGE PROPERTIES

Water addition requirements, wt.%	9.5
Recommended use limit °C (°F)	1760 (3,200)
Lbs. required to place one ft^3.	160
kg required to place one m^3	2600
Specific gravity, fired @ 980°C (1,800°F)	2.5

Condition (Treatment)	Cold Crushing Strength (psi)	Cold Crushing Strength (kPa)	Permanent Linear Change, %
Dried 24 Hrs. @ 104°C (220°F)	900	131	-0.1
Fired 5 Hrs. @ 816°C (1,500°F)	2,000	290	-0.2
Fired 5 Hrs. @ 1094°C (2,000°F)	4,000	580	-0.2
Fired 5 Hrs. @ 1700°C (3,100°F)	5,500	798	+0.4

Chemical analysis, % fired basis

Alumina	Al_2O_3	81.2
Silica	SiO_2	13.9
Ferric oxide	Fe_2O_3	1.6
Titania	TiO_2	2.2
Alkalies, as	Na_2O	0.5

Thermal conductivity		Btu in./ft^2 hr °F	J/m hr K
Mean temperature	@ 260°C (500°F)	7.8	4047
	@ 540°C (1000°F)	7.9	4098
	@ 816°C (1500°F)	7.9	4098
	@ 1094°C (2000°F)	8.3	4306

TABLE 3. LIGHTWEIGHT CASTABLE PHYSICAL PROPERTIES

Maximum service Temperature	3,000°F	1649°C
ASTM Class C-401		
Dry castable required	88 lbs/ft^3	1412 kg/m^3
Water required for Pouring (approximate)	3 1/4 to 3 1/2 gal/100 lbs	300 g/kg
Bulk density after Drying at 230°F (110°C)	92 lbs/ft^3	1476 kg/m^3
Modulus of rupture after	Lbs/in.^{2}	kPa
Drying at 230°F (110°C)	150 to 250	22 to 36
Heating at 1,000°F (540°C)	50 to 100	7.3 to 15
Heating at 1,500°F (816°C)	100 to 150	15 to 22
Heating at 2,700°F (1,480°C)	700 to 1300	102 to 189
Cold crushing strength after	Lbs/in.^{2}	kPa
Drying at 230°F (110°C)	500 to 1000	73 to 145
Heating at 1,000°F (540°C)	400 to 600	58 to 87
Heating at 1,500°F (816°C)	500 to 770	73 to 112
Heating at 2,700°F (1,480°C)	2100 to 2600	305 to 377
Heating at 900°F(1595°C)	2100 to 2800	305 to 406
Reheat test, permanent Linear change, percent after		
Drying at 230°F (110°C)	Negligible	
Heating at 1,000°F (540°C)	0.0 to -0.2	
Heating at 1,500°F (816°C)	0.0 to -0.2	
Heating at 2,900°F (1,590°C)	-1.0 to +1.5	
Thermal conductivity	Btu/hr ft^2 °F/in	J/m hr K
500°F (400°C)	3.48	1805
1,000°F (600°C)	3.61	1873
1,500°F (800°C)	3.87	2008
2,000°F (1,000°C)	4.20	2179
Chemical analysis (Approximate %) (Calcined Basis)		
Silica (SiO_2)	35.0	
Alumina (Al_2O_3)	57.3	
Titania (TiO_2)	1.7	
Iron Oxide (Fe_2O_3)	1.1	
Lime (CaO)	4.1	
Magnesia (MgO)	0.1	
Alkalies ($Na_2O + K_2 + Li_2O$)	0.7	

TABLE 4. UNISTIK CEMENT

Physical properties:	Unistik A
Appearance	Gray
Type	Wet Airset
Use limit, °C (°F) w/module	1,540 (2,800)
kg (lbs) required per module	1.4-1.8 (3-4)
For use with	Plastic dense castable firebrick
Chemical analysis (%)	**Unistik A**
Alumina (Al_2O_3)	37.0
Silica (SiO_2)	57.0
Iron oxide (Fe_2O_3)	1.0
Titania (TiO_2)	1.0
Alkalies ($Na_2O + K_2O$)	3.0
Trace inorganics	1.0

A conceptual design of the regenerable precombustor design using the zirconia coating is shown on Figure 19. The precombustor is a double shell design with an annular space for cooling air which is also the combustion air for the primary burner. The inner shell, which is also the combustor wall is covered with the composite layer. The metal fiber material is also a thermal barrier with significantly lower thermal conductivity. Nevertheless, extensive cooling is required to maintain acceptable temperatures at the combustor inner shell.

A thermal analysis of the regenerable design was done to determine if the temperatures were within the design limits. Figure 20 shows the respective heat fluxes. A heat balance shows that for a regenerative air velocity of 3 m/s (9.8 ft/s), and a coating thickness of 1.2 mm (0.3 in), the metal temperature is 200°C (391°F). The results show that the regenerable design is practical from a thermal performance standpoint. The primary development which is needed is in the coating technology as applied to larger sizes. Currently, only smaller gas turbine size applications have been made.

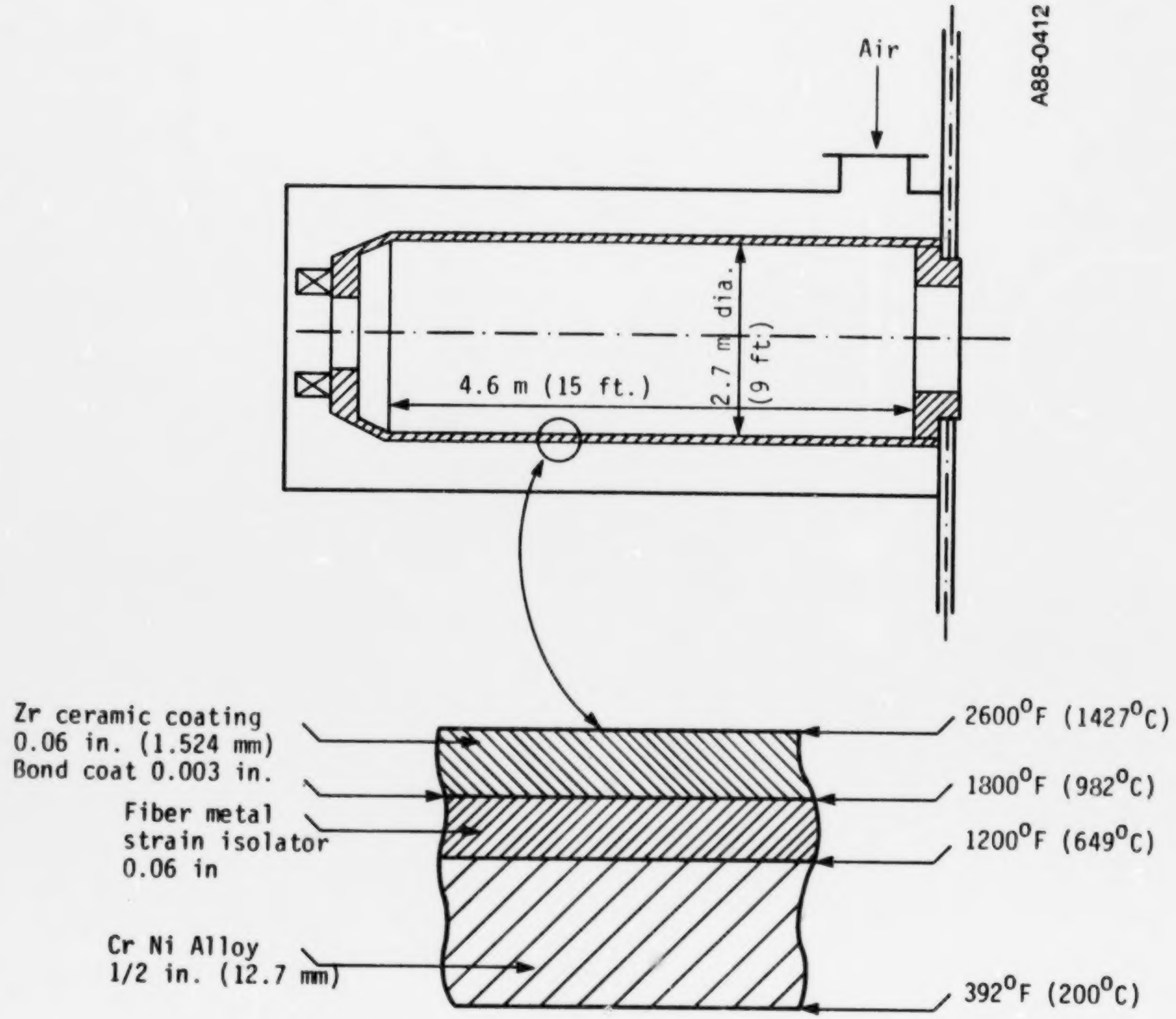

A88-0412
Air
4.6 m (15 ft.)
2.7 m dia. (9 ft.)
Zr ceramic coating
0.06 in. (1.524 mm)
Bond coat 0.003 in.
Fiber metal
strain isolator
0.06 in
Cr Ni Alloy
1/2 in. (12.7 mm)
2600°F (1427°C)
1800°F (982°C)
1200°F (649°C)
392°F (200°C)

Figure 19. Regenerative low-NO_x combustor design: 59 MW (200 MMBtu/hr) capacity.

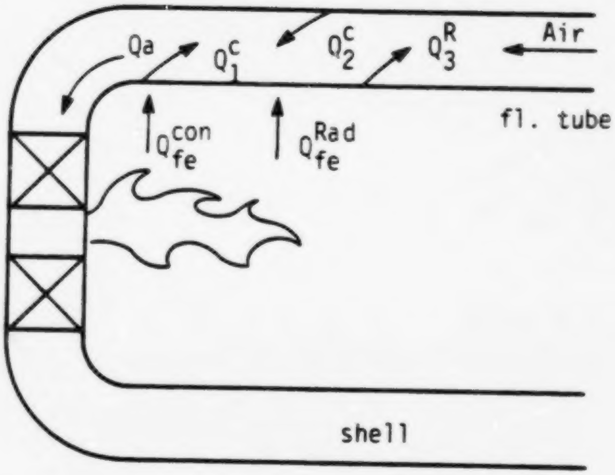

Qa
Q_1^c
Q_2^c
Q_3^R
Air
fl. tube
Q_{fe}^{con}
Q_{fe}^{Rad}
shell

Figure 20. Heat transfer scheme regenerative design.

SECTION 3

COMBUSTOR AND RETROFIT DESIGN

This section presents the low-NO_x precombustor design and boiler retrofit based on the concepts raised in Section 2. This design is intended to be as adaptable as practical to the general class of industrial package boilers in the 15 to 29 MW (50 to 100 MMBtu/hr) thermal input capacity range. Despite the adaptability, there are two boiler interfaces which will be specific to the boiler which is being retrofit. The integration of the control system to the existing boiler and plant controls will also have site-specific aspects. Within that context, the design presented here is a detailed generic design.

The parameters that ultimately determine the equipment configuration are the following with associated ranges considered:

- Capacity 15 MW (50 MMBtu/hr) (nominal) to 59 MW (200 MMBtu/hr) thermal input
- Fuel – gas, No. 2 fuel oil, No. 6 fuel oil, waste fuels
- Maximum permissible emission levels i.e., NO_x
- Site interface requirements -- boiler size and type, site layout and integration requirements

The capacity of the boiler will influence the size of the burner and associated fuel train whereas the control system would be identical in all cases with the exception of different customer-required safety system interlocks. Capacity of the boiler influences the residence time in the first stage precombustor which has been addressed in the design by providing modular spool pieces in the combustion section.

The different fuels will impact the requirement of residence time in the precombustor and minimum inside diameter of the combustion section. Flame impingement on the walls was considered in selecting the final configuration. Since the design utilizes a modular approach, customization of each combustor is not going to significantly impact cost. The size and cost of the equipment will always be produced on order rather than to inventory. Suitable components may be stocked and combined on order. This is the typical operation mode of large equipment vendors. The automobile industry too has adopted "just in time" inventory management to reduce financing cost and to prevent the obsolescence of inventories items by advances in the technology.

Site requirements will dictate the maximum size of the first stage precombustor and how equipment may be arranged in the equipment halls. Each installation is likely to have its own unique individual requirements that must be addressed on a case-by-case basis. The equipment modules may be the same, but how they are arranged is likely to be customized as the real estate allows.

Figure 21 shows the process diagram for a nominal 15 MW (50 MMBtu/hr) boiler with low-NO_x burner system in place and the associated process flows. This combustor is shown firing No. 6 fuel oil and high nitrogen waste. Figure 22 shows a cross-section of the first stage precombustor and some details of the internal configuration. Full design drawings are supplied in Appendix C.

The low-NO_x burner system can be divided into several main subsystems as follows:

- Burner
- First stage precombustor
- Fuel and combustion air valve train
- Auxiliary equipment
- Control and data acquisition system

Examination of the various classes of subsystems reveals that some fall into the category of conventional equipment already utilized on combustion equipment. The primary components of interest are the burner, first stage precombustor, and the control and data acquisition system. Of additional interest is which modifications need to be made to existing boilers in a retrofit operation to install a low-NO_x burner system. The subsystems of particular interest are discussed in greater detail in the following sections.

An important consideration when evaluating the cost of the low-NO_x burner system compared to other systems is the incremental cost of this type of control system. It should be expected that the cost of burner, fuel and combustion air valve train, and auxiliary equipment is virtually identical to that of a standard boiler installation. Increased costs are due to the first stage precombustor, modifications to existing boiler front walls, the installation of additional sidefire staged air ports, and an increase in the cost of the control system and valve train due to increased control logic requirements.

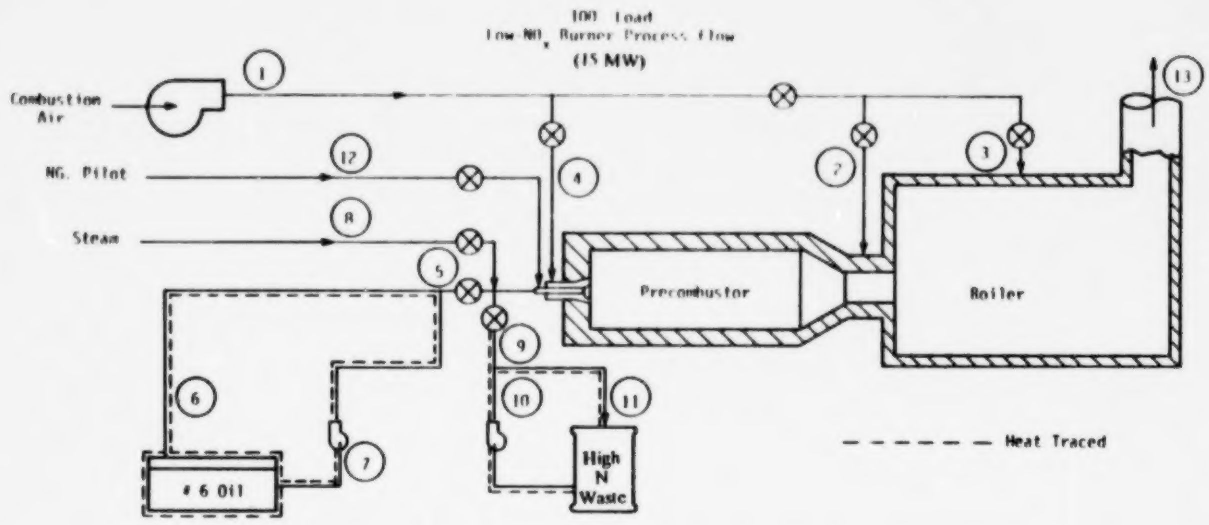
Real estate requirements may be important if buildings have to be enlarged or no space is available. Whether these costs should be included is a question that is likely to be site specific. It is possible to orient the precombustor vertically with a suitably designed elbow at the transition section to the boiler. This configuration could be used at a site with limited horizontal front wall access.

3.1 BURNER

The burner for this application is of standard design. NO_x control is achieved by controlling the air/fuel ratio in the first stage precombustor and the subsequent injection of air at the throat or in the main combustion chamber. A register burner with adjustable louver blades is specified. This type of burner offers capabilities for flame shaping and provides high turn-down ratios. Fuel atomizers are installed as the case may require for the various fuels and wastes. Large variations in viscosities require the adjustment of nozzle sizes as well as adjustment in atomizing air or steam pressure. Figures 23 and 24 show typical burner and atomizer configurations.

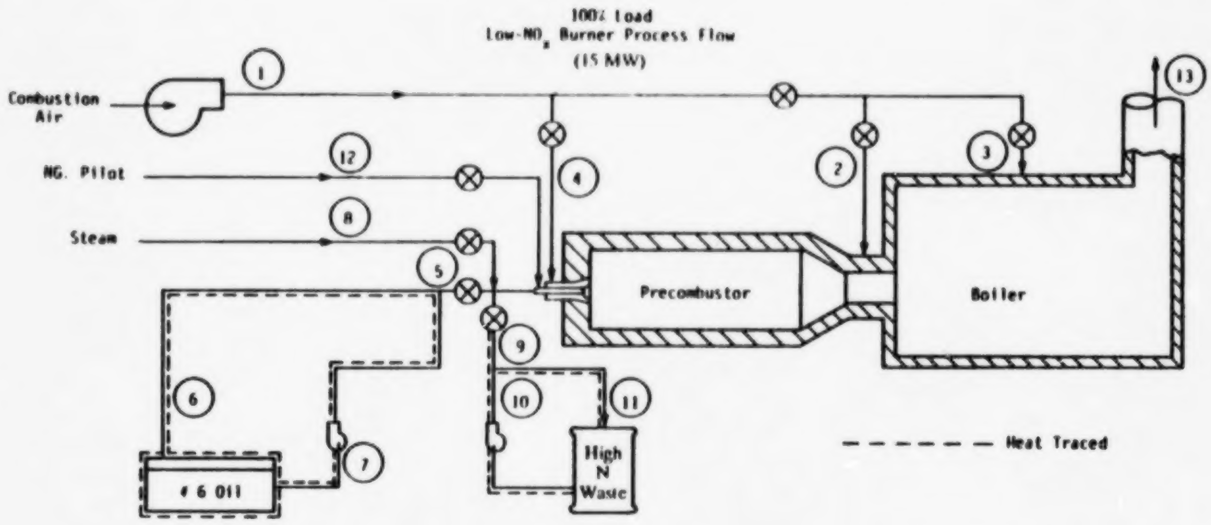
3.2 FIRST STAGE PRECOMBUSTOR DETAIL

The ideal installation of the precombustor will provide for access as typically found on a shell and tube heat exchanger. The entire structure is mounted on wheels to allow for thermal expansion along its length and also for inspection access. The valve train and burner controls


100 Load
Low NO$_x$ Burner Process Flow
(15 MW)
Combustion Air
NG. Pilot
Steam
1
2
3
4
5
6
7
8
9
10
11
12
13
Precombustor
Boiler
# 6 Oil
High N Waste
Heat Traced

Stream #	1	2	3	4	5	6	7	8	9	10	11	12	13
Fluid	AIR	AIR	AIR	AIR	#6	#6	#6	STEAM	WASTE	WASTE	WASTE	NG	FLUE
P_{NOM} ± (psig)	1	1	1	1	100	100	100	100	100	100	100	60	0.1
T_{NOM} ± (°F)	70	70	70	70	220	220	220	220	220	220	220	70	400
M_{NOM} (KIPS/HR)	42	7	7	28	3	2	5	0.35	1.25	0.8	0.45	0.05	45
P_{MAX} (psig)	1	1	1	1	150	150	150	150	150	150	150	60	0.1
T_{MAX} (°F)	150	150	150	150	250	250	250	250	250	250	250	110	500
M_{MAX} (KIPS/HR)	45	8	8	30	4	3	6	0.5	3	3.5	3.5	0.1	50

Figure 21a. Process diagram – English units.


100% Load
Low-NO$_x$ Burner Process Flow
(15 MW)
Combustion Air
NG. Pilot
Steam
Precombustor
Boiler
# 6 Oil
High N Waste
Heat Traced
1
2
3
4
5
6
7
8
9
10
11
12
13

Stream #	1	2	3	4	5	6	7	8	9	10	11	12	13
Fluid	AIR	AIR	AIR	AIR	#6	#6	#6	STEAM	WASTE	WASTE	WASTE	NG	FLUE
P_{NOM} ± (kPa)	.15	.15	.15	.15	14.5	14.5	14.5	14.5	14.5	14.5	14.5	8.7	0.01
T_{NOM} ± (°C)	21	21	21	21	105	105	105	105	105	105	105	21	205
M_{NOM} (Tonnes/hr)	19.1	3.2	3.2	12.7	1.4	0.9	2.3	0.16	0.6	0.4	0.2	0.02	20.5
P_{MAX} (kPa)	.15	.15	.15	.15	21.8	21.8	21.8	21.8	21.8	21.8	21.8	8.7	0.01
T_{MAX} (°C)	66	66	66	66	121	121	121	121	121	121	121	44	260
M_{MAX} (Tonnes/hr)	20.5	3.6	3.6	13.6	1.8	1.4	2.7	0.23	1.4	1.6	1.6	0.05	23

Figure 21b. Process diagram – S.I. units.

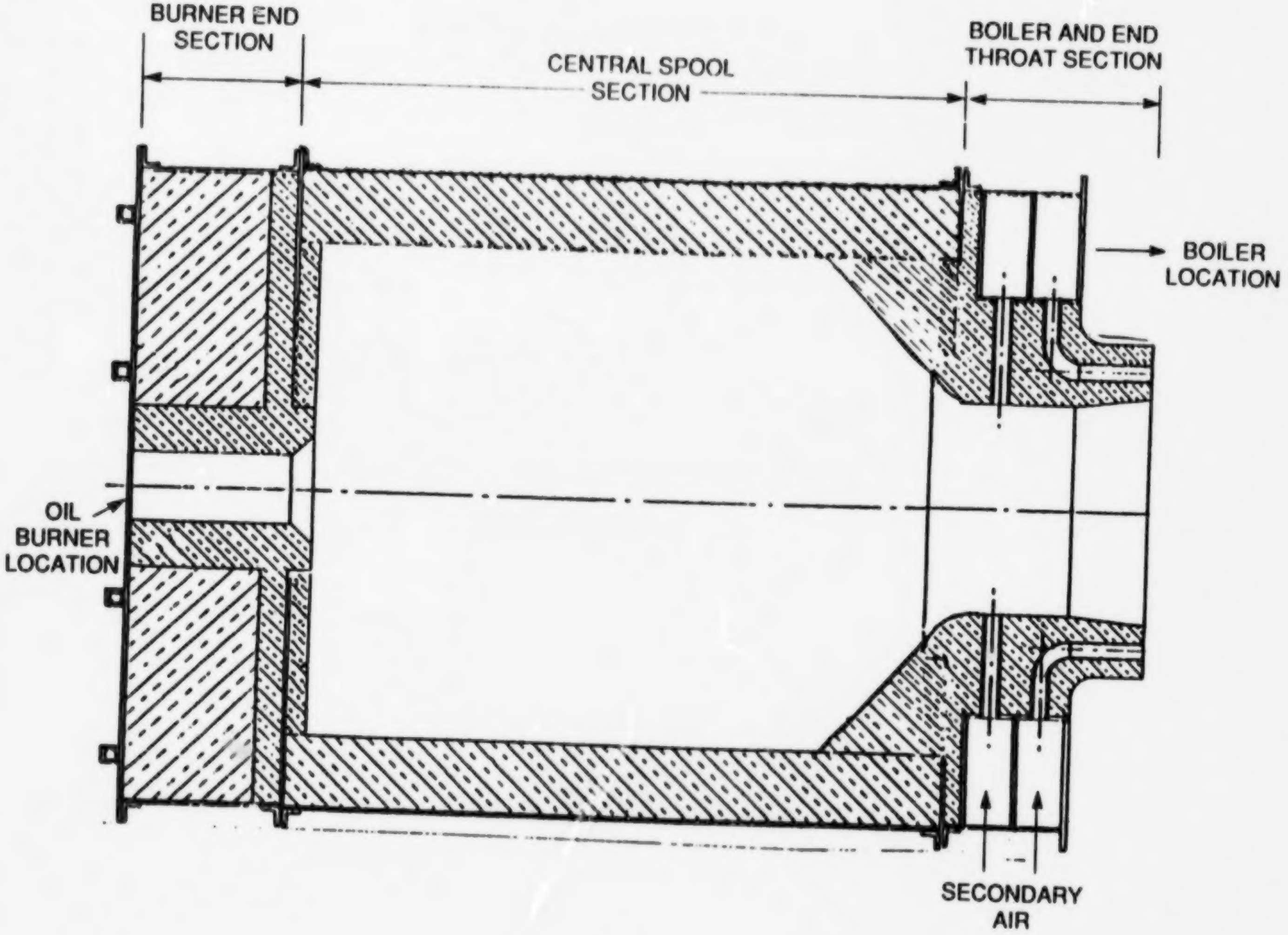
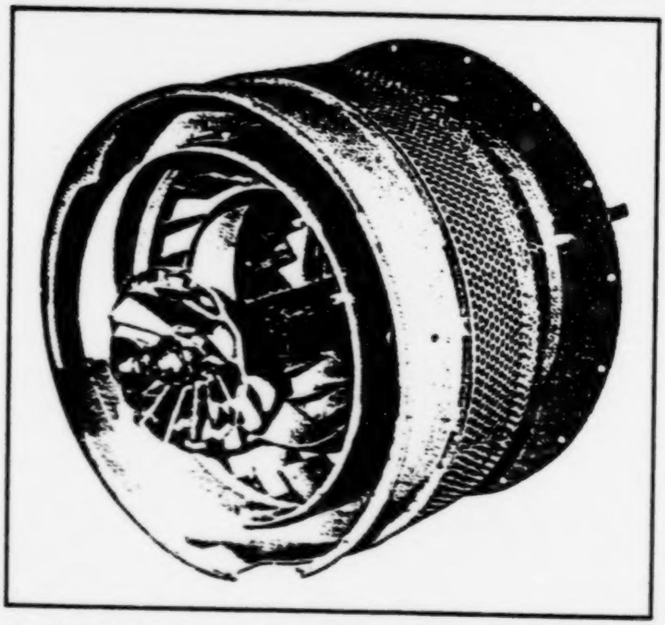

BURNER END SECTION
CENTRAL SPOOL SECTION
BOILER AND END THROAT SECTION
BOILER LOCATION
OIL BURNER LOCATION
SECONDARY AIR

Figure 22. The combustor section.

Coen Register Burner

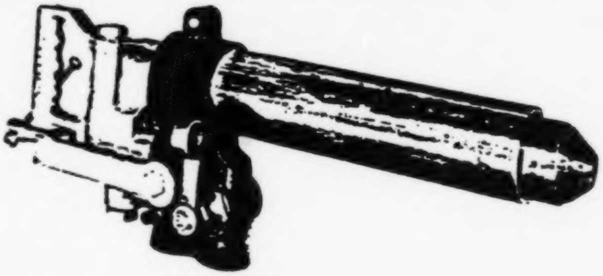


The Coen register is designed with adjustable louver blades to provide optimum combustion efficiency coupled with wide turndown ability. With Coen's proven design and rugged construction the register burner will provide years of trouble free service.

- Available with integral scroll for low BTU gas or coal requirements.
- Engineered to meet low NOx emission standards for each application as required.
- Available as integral part of single burner package or for multiple burner applications.
- Available with ring type or multiple spud type gas burner elements.

Figure 23. Example register burner.
(Courtesy of the Coen Company)

Coen Atomizers



Coen offers three types of atomizers, each in several sizes, to handle fuel oils or liquid wastes:

Coen MV Atomizer

- Inside mix steam/liquid atomizer.
- Four sizes available for flow rates up to 35 gpm with steam pressures of 100 to 200 psig, each with wide range capability.
- Atomizes liquids from low viscosity up to 500 SSU.
- Capable of producing special asymmetrical spray patterns.

Coen MA Atomizer

- Low pressure inside mix air/liquid atomizer.
- Four sizes available for flow rates up to 25 gpm, with air pressures from 5 to 15 psig, each with wide range capability.
- Preferred method of atomization when steam is not available.
- Ideal for corrosive or low flash point liquids, up to 300 SSU.
- Capable of producing special asymmetrical spray patterns.

Coen SNC Atomizer

- Outside mix steam/liquid atomizer.
- Two sizes available for flow rates up to 12 gpm with atomizing steam at 150 psig.
- Atomizes high viscosity sludges or liquids with large particles, up to ¼" diameter.

Figure 24. Example atomizer.
(Courtesy of the Coen Company)

are mounted on a separate rack or structure to the side of the precombustor rather than on the back or near the burner end section. With this configuration arrangement, changes in the length (residence time) for low-NO_x control can be easily accommodated. Typically, an installation will only be as long as is needed to achieve the desired emission control requirements.

The precombustor section consists of several main modules that can be combined to provide optimum operation of the system for low-NO_x emissions. The top assembly drawing on Figure 22 shows a section of the three main components: the burner end section, the central spool section and the boiler end and throat section. Each component has been designed to provide the needed prototype flexibility to adjust operating conditions for optimum operation.

The burner end section will be configured to accommodate the burner size requirements while providing a standard bolt interface to the central section spool pieces. The maximum surface temperature permissible is 1540°C (2800°F). The length of the combustor can be adjusted by installation of different one-piece center sections or by the combination of various standard center sections. It is desirable to minimize the number of seams and for this reason it is recommended to minimize the number of center sections. Regenerative designs had initially been considered; however, the complexity of joints and parts in general would have resulted in significantly higher costs and much lower configuration flexibility for the refractory chosen.

The central section has been designed to be provided in several basic lengths. They are 0.91, 2.5, and 2.9 m (36,100 and 116 in.). Other section lengths could be provided if needed.

The configuration of the lightweight insulation material provides good thermal response and compatibility with boiler requirements in terms of response time. The insulation system will provide for quick start-up (15 min.), easy installation, and has been demonstrated on industrial furnaces. Sections 2.2 and 2.3 summarize the maximum use temperatures, the long term use limits and the method by which the insulation material is held in place with anchoring ceramic tubes. The burner end section utilizes a combination of Pyro-Bloc H and lightweight castable refractory. The combination of these materials will provide the needed abrasion resistance in the areas where it is needed. Also, the castable base material will provide higher heat conduction to keep the Pyro-Bloc temperatures within design limits.

The expected operating temperature of the inside wall can be controlled well by controlling the stoichiometric ratio in the precombustor. Figure 7 shows the relationship of combustion temperature with stoichiometric ratio. Control is addressed in Section 3.4.

3.3 BOILER INTERFACE

The precombustor is joined to the boiler via the boiler end section. The boiler end section serves a number of functions. It serves as a bolting arrangement to fasten the precombustor spool pieces to the boiler, restrict the precombustor flow and allow for the addition of secondary air either axially or tangentially. The large diameter throat is necessary to lower the gas to typical boiler gas velocities of 36.6 m/s (120 ft/sec) in the region.

The throat is made from lightweight refractory to improve the abrasion resistance. Sharp corners have been avoided to reduce the chance of fracture. At the boiler interface, tubes have been formed around the throat to help cool the gas and maintain temperatures to the maximum acceptable levels at the air injection plenum which is fabricated from stainless steel. The injection tubes will be allowed to burn out if metal service temperatures are exceeded without detriment to their function. Future product designs may see some reduction in the complexity of the throat design if it is found that the all stage air can be injected at the sidefire air ports. Details of the boiler end section are shown in Appendix C. Final air duct routing will depend on the site specifications when known.

3.4 CONTROL SYSTEM AND DATA ACQUISITION

3.4.1 Introduction

The normal product development path typically results in the design and construction of the product at various stages of maturity. Only in the simplest cases is a final product reached in the first design cycle. The design of the control system for the low-NO_x burner is no exception. It does not fall into the "simple" category and it is prudent to provide for initial control flexibility in the prototype that will allow for the tuning of control loops and easy modification of the control strategy after initial operation when the true characteristics of the combustor and precombustion chamber become known. A trade-off is usually made between analytical and empirical evaluation to determine the expected performance. Actual operation, however, always determines whether the analysis conducted was correct or not. The "extra" initial control flexibility provided increases the cost of the first control system, but also insures that all objectives can be met at minimum system development cost.

It should be expected that the final control system configuration can be implemented in a very cost effective way utilizing state of the art microprocessor technology and programmable logic controllers.

The initial prototype system will also have a greater need for more data aquisition than will be required of the product version to permit the proper evaluation of system performance. Optimization of cost can only occur, when all the operating parameters are fully understood. For this product this leads to a disproportinately high initial control and data aquisition cost in the prototype. This should be viewed as an intermediate step toward the final system configuration which would be cost effective.

At least three control system suppliers presently offer competitive, easily configurable distributed microprocessor based control systems. These microprocessor systems are capable of automating entire production processes provided they are equipped with the appropriate input-output modules and may be seen as an overkill for the application. Experience with alternative lower cost IBM-PC based control systems, however, has shown that the cost of programming is very substantial indeed, often exceeding the cost of the initial system many times. The overall cost of the control system must be considered to come to a fair conclusion whether it is cost effective. Due to the flexibility that has been built into these systems the advantages of the microprocessor system as development tools for the prototype are overwhelming compared to a simple PC system. Data aquisition can also be accomplished by the microprocessor systems and various reports printed as required. Data can also be downloaded to other computer facilities for further evaluation and processing. Some complete systems offer I/O modules at IBM-PC competitive prices making the integrated control system and data aquisition option very attractive.

3.4.2 Control Strategy

The burner management system consists of an integrated set of control strategies that address the need for safety, equipment operating limitations, optimum operating conditions, and regulatory requirements.

- The burner management system will incorporate a primary flame safeguard relay to provide the standard and typical safety interlocks addressing the need for purge cycles, flame sensing, and start-up.
- An integrated multitasking control system will provide system interlocks and PID controls to maintain appropriate air/fuel ratios and heat rates for low-NO_x and soot emissions and regulate capacity requirements.
- Additional control loops are utilized to monitor precombustor operating conditions such as temperature, staging air, and waste feed permissive signals.
- Operating constants for stage air, waste feed percent, precombustor temperature set points or gradients, and minimum waste feed combustor temperature can be changed in the prototype easily by the operator. An evaluation needs to be made upon final system configuration determination what parameters should be fixed and which should be changeable by operators.

The control system configuration is shown in schematic form in the process and control instrumentation diagram drawing number 8023-001 shown in Appendix C. A typical fuel train reflecting a similar degree of complexity is shown in Figure 25. This diagram reflects the capability to fire either No. 2 or No. 6 fuel oil in conjunction with waste fuels. This system is set up to allow air and fuel ratios to be adjusted completely independently a feature that may not be required of a product once the exact operating characteristics are known. The functions of all the control loops will be discussed in detail in the following paragraphs. Future controls may also incorporate the use of "ganged" valves to reduce costs of operating control channels and valve operators. It should be expected that the control system for the low-NO_x burner will be more complex than that of a conventional burner of similar size and capacity due to the complex operating requirements during start-up and the requirement to closely monitor and adjust the fuel/air ratios to maintain tight temperature control in the precombustor section.

There are a number of operating constraints that must be satisfied to meet the objectives of low-NO_x, achieve the destruction of fired waste materials, and at the same time also satisfy other regulatory requirements. Parameters that must be observed in particular are:

- Up to a maximum of 50 percent total heat input may be derived from waste fuels.
- Waste fuel firing must be discontinued if the temperature in the precombustor drops below a predefined value no longer insuring the destruction of waste components.
- Waste firing is not permitted at a load below 25 percent of full capacity.
- The wall temperature in the precombustor may not exceed 1540°C (2800°F)
- During normal operation the air/fuel stoichiometric ratio must be maintained in the range of 0.7 to 0.9 for low thermal NO_x formation in the precombustor. Upon leaving the precombustor, while the remaining air is added, temperatures must be reduced quickly to prevent formation of second stage thermal NO_x but still ensure soot burnout. Proper mixing of the additional air must be assured in the precombustor/main combustor nozzle and/or at the sidefire air staging nozzles.

The critical relationships that should be observed to minimize NO_x are summarized in Section 2.2. For this combustion design, these conditions will also provide an environment highly conducive to good waste destruction. The time-temperature conditions in the low-NO_x mode are far superior to the thermal destruction environment in a typical boiler. A typical boiler cofiring waste has been shown to provide a waste destruction efficiency averaging 99.998 percent. The present design should improve on this efficiency. In addition, and very significantly, the current design should also emit much lower levels of products of incomplete combustion (PICS).

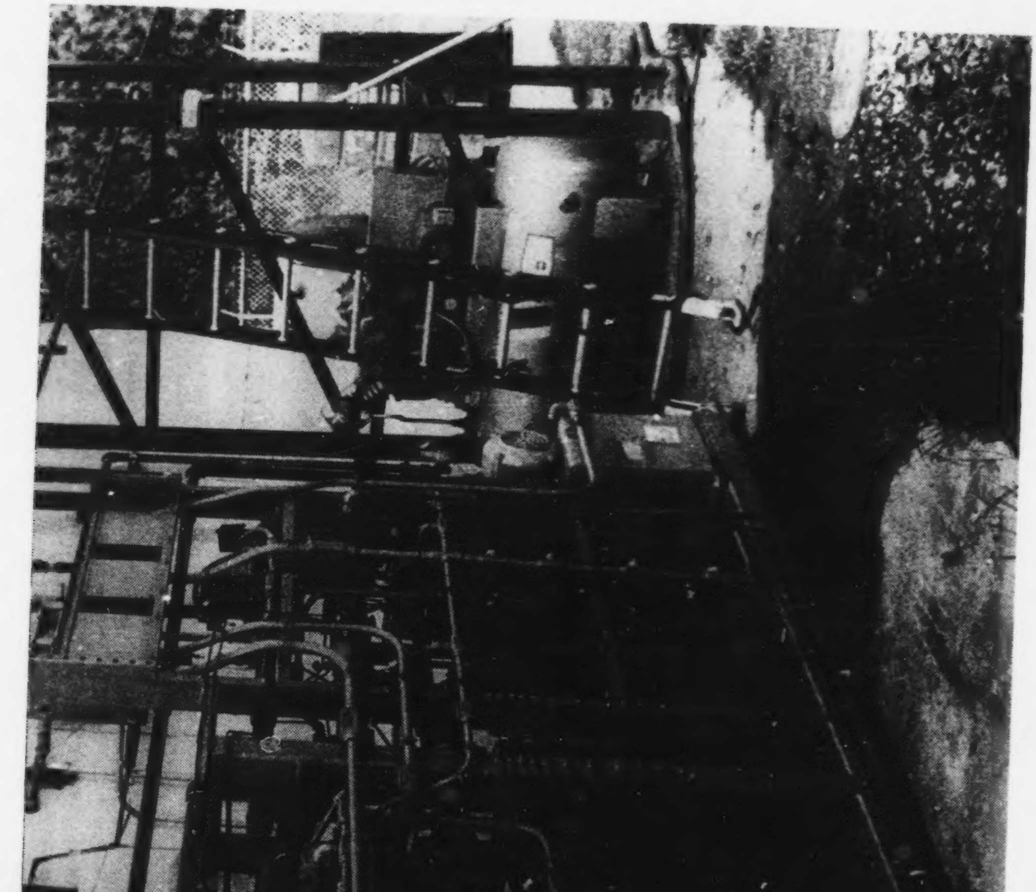


Figure 25. Typical fuel train.

The Section 2.2 material showed that if the stoichiometric ratio is maintained around 0.7, NO_x emissions will be minimized and the refractory temperature limits will be maintained. Upon the addition of the remaining second stage air it is essential to reduce the temperature quickly to maintain the low emission levels desired.

The relationship of NO_x emissions to first-stage residence time shows that longer residence times result in lower emissions rates. Since the combustor volume is fixed, lower firing rates should result in lower ppm emission rates. For this type of staged combustion burner, the levels of NO_x emissions are virtually unaffected by the amount of fuel nitrogen which leads to the conclusion that this type of burner is ideally suited for the combustion of high nitrogen waste fuels. All of the above considerations are integrated into the control system strategy to minimize emissions during all phases of operation including start-up, normal operation, load changes, shut-down, emergency shut-down, and during fuel switching.

The process and instrumentation diagram reflects five primary process streams. They are natural gas, No. 2 fuel oil, No. 6 fuel oil, waste fuels, and air. It is envisioned that the combustor will be operated primarily with a combination of No. 6 fuel oil and waste fuels and that No. 2 fuel oil and gas would only be used during the start-up phase of operation. This does not mean that the combustor cannot be operated on other fuels but that the primary benefit would be derived in terms of emission reductions from operation with these fuels.

The operation sequence is outlined following explaining the normal start-up, operation and shut-down of the facility in principle. Detailed control loops must be defined in a control specification document. To help understand the procedure it is helpful to know that ratio control valves are employed to adjust the fuel air ratios for the various fuels and that excess air is introduced via air by-pass valves.

3.4.3 Start-up, Operation and Shut-down Control Sequence

1. The start-up sequence may begin when the system interlocks show no alarm condition that would prevent operation of the burner. Status of these interlocks allows the flame safeguard relay to permit the start of the start-up sequence after receipt of the start sequence.

2. Valves and other control elements are properly set by the control system to perform and monitor a purge cycle. Upon completion of the number of volume changes in the combustor, the flame safety relay will open the pilot air and gas valve and light the pilot light.

3. Upon successful ignition verified by the flame sensor, the flame safeguard relay will permit the operation of the main No. 2 fuel and air valve. Flame failure detection will result in another purge cycle.

4. The main and bypass air valves and No. 2 fuel valve are opened and firing proceeds at approximately 3 percent excess air in the precombustor for warm-up. The main air flow maintains the fuel flow at .7 to .9 stoichiometric ratio via the ratio control valve while additional air is introduced via the air bypass. The fuel firing rate is determined by the maximum heating rate previously programmed into the control sequence.

5. Two additional control loops are particularly important at this time monitoring excess air conditions and the precombustor temperature. The excess air monitor

generates a signal that is compared to the set point and the excess air control loop adjusts the excess air as required. The precombustor temperature is monitored by the temperature control loop that also interacts with the fuel firing rate controller. At a predetermined temperature, No. 2 fuel firing may be switched to No. 6 fuel oil by switching the fuel main solenoids and also switching the fuel ratio sensing three-way valves.

6. As the temperature in the precombustor approaches the maximum operating temperature, bypass air to the precombustor is reduced and introduced as second-stage air in the main orifice area or into the main combustor as the control strategy requires. Lower stoichiometric ratios reduce the maximum combustion temperature while also reducing NO_x emissions.

7. Waste fuel firing can be implemented anytime the combustor is operating at 25 percent or higher capacity and the minimum combustion temperature for waste firing is attained in the precombustor. Waste firing is initiated by opening the appropriate waste fuel air control valve and simultaneously closing the main fuel air valve. Proportional main fuel and waste fuel firing is maintained by the proportional control valves.

8. Load following is accomplished by the main air flow control valve which controls the airflow for main fuel, waste fuel and stage air. Reduced air flow due to throttling by this valve results in lower pressure drops across the ratio control valve orifices causing proportional reductions in main and waste fuel flow and proportional reduction in stage air flow. The important feature to observe is that the relative positions of valves are not changed. The main to waste fuel ratios are maintained. An additional capability provided by this control system and the piping arrangement is the capability to fire waste at a fixed firing rate while the main fuel is modulated to provide load following. This is the firing mode often used by operators, because the control capabilities of the existing systems can not provide for the previously discussed methodology. The draw-back of the latter system is that the full waste destruction capability of the system is not utilized.

9. Normal system shutdown is accomplished by reducing main air flow which in turn causes waste fuel firing to be stopped when the 25 percent capacity level is breached. As capacity is decreased further, the temperature in the precombustor will be lowered resulting in stage air reduction and stoichiometric firing in the precombustor until stage air is reduced to zero. Further firing rate reduction will result in cooling of the precombustor at the predetermined cooling rate resulting in the eventual shut-down of fuel flow. Cooling of the facility may continue by air circulation or as desired.

10. Emergency shut-down is accomplished by closing all fuel valves simultaneously but maintaining air circulation. Emergency shut-down would most likely be triggered by the flame safety relay due to loss of flame or some other system malfunction that would cause the flame safety relay to act.

3.4.4 Data Acquisition

The control system will also be able to serve as an integrated data aquisition system. Many of the input control channels may double as data aquisition channels. Since formatting and time sequences can be fully integrated, no compromise in reliability will result.

3.4.5 Control System Specification

A specification of the control system meeting the needs of the prototype low-NO_x combustor follows. A detailed listing of the required input/output channels is also presented in Table 5, not accounting for possible channels required for the boiler or other system requirements.

3.4.6 Control System Requirements

General

The control system to be supplied shall consist of a complete process automation system that includes all the control functions (software) and hardware to permit automation of the test operation of the low NO_x combustion burner system. The system shall have sequential, logic, loop and multivariable control functions completely integrated. Each shall be capable of interacting with the others. Sequential control shall be able to turn loops on and off, open or close cascades, and set alarm limits or setpoints. Logic shall be able to change the sequential operation based on process changes or interlocks, or shut the process down upon emergency conditions. Multivariable control shall set continuous loop set-points or output directly to actuators. All values shall be directly accessible by all automation functions.

The control system shall be complete within its own operating system software, so that the test engineer can configure the control strategies without writing any computer code. The control system should employ enhanced concepts to expedite procedure strategy definitions that are presently available in Computer Aided Design (CAD) systems. Since the low-NO_x burner system is a prototype and would be used to optimize operation and define a final product, a system offering user-friendly approaches is important. Therefore, the control system design should allow for minimum configuration or set-up time and maximum operation or test time. Current information indicates that CAD-type versus high level language type set-up systems offer the most efficient use of available test time.

The control system should be designed to allow for ease of start-up and commissioning. It is desired that the system be designed to minimize the possibility of human error in configuration or set-up; i.e., avoid reuse of already named inputs, multiple loop calculations trying to control one common control output, use of unrelated variables in a control state, etc.. After various test and operational procedures have been defined, accepted, and implemented, the system will need to be operated by non-engineering oriented, as well as engineering oriented personnel.

The preferred concept of the control system would consist of (1) one touch screen color graphics display, multiple remotely located process controllers, multiple varied I/O modules connected to their associated controllers, and controller and I/O module uninterruptible power supply capability. System components shall be designed to reduce installation, replacement, and maintenance costs.

Report Generation

The control system, being used as an optimization tool for the prototype low-NOx burner system, must be able to generate various summary reports and allow the developer to efficiently evaluate his or her procedures. A system automatically generating its own reports would be preferred. A system that categorizes its reports to I/O, controllers, work station, and process variables has significant advantages. Examples of suggested type reports are as follows:

TABLE 5. SUMMARY OF INPUT/OUTPUT SIGNALS FOR LOW-NO$_x$ BURNER SYSTEM

TAG NAME	DESCRIPTION	FLUID	SIGNAL	TYPE
PSL- 211	LOW GAS PRESSURE	GAS	CONTACT	I
PSL- 174	LOW #2 OIL PRESSURE	#2 OIL	CONTACT	I
PSL- 173	LOW #6 OIL PRESSURE	#6 OIL	CONTACT	I
PSL- 172	LOW WASTE PRESSURE	WASTE	CONTACT	I
V- 203	GAS SHUT-OFF	GAS	115 VAC	O
V- 205	GAS SHUT-OFF	GAS	115 VAC	O
V- 204	GAS VENT	GAS	115 VAC	O
V- 208	PILOT AIR SHUT-OFF	AIR	115 VAC	O
HS- 304	#2 PUMP START/STOP	#2 OIL	115 VAC	O
V- 153	#2 FUEL OIL SHUT-OFF	#2 OIL	115 VAC	O
HS- 303	#6 PUMP START/STOP	#6 OIL	115 VAC	O
V- 165	SIGNAL DIVERTER VALVE	AIR	115 VAC	O
V- 166	SIGNAL DIVERTER VALVE	AIR	115 VAC	O
V- 157	#6 FUEL OIL SHUT-OFF	#6 OIL	115 VAC	O
HS- 302	WASTE PUMP START/STOP	WASTE	115 VAC	O
V- 167	WASTE SHUT-OFF	WASTE	115 VAC	O
HS- 301	BLOWER START/STOP	AIR	115 VAC	O
FCV- 102	MAIN AIR CONTROL FORWARD	AIR	115 VAC	O
FCV- 102	MAIN AIR CONTROL REVERSE	AIR	115 VAC	O
FCV- 109	BYPASS PRE-COMB FORW	AIR	115 VAC	O
FCV- 109	BYPASS PRE-COMB REV	AIR	115 VAC	O
FCV- 133	WASTE COMB AIR FORW	AIR	115 VAC	O
FCV- 133	WASTE COMB AIR REV	AIR	115 VAC	O
FCV- 130	STAGE I COMB AIR FORW	AIR	115 VAC	O
FCV- 130	STAGE I COMB AIR REV	AIR	115 VAC	O
FCV- 132	STAGE II COMB AIR FORW	AIR	115 VAC	O
FCV- 132	STAGE II COMB AIR REV	AIR	115 VAC	O
PT- 104	BLOWER OUTPUT PRESSURE	AIR	4-20 MA	I
DPT- 105	TOTAL AIR FLOW	AIR	4-20 MA	I
PT- BP	BOILER PRESSURE	STEAM	4-20 MA	I
DPT- 107	PRE-COMB MAIN FUEL AIR	AIR	4-20 MA	I
DPT- 106	PRE-COMB BY-PASS AIR FLOW	AIR	4-20 MA	I
DPT- 126	PRE-COMB WASTE AIR FLOW	AIR	4-20 MA	I
PT- 128	PLENUM AIR PRESSURE	AIR	4-20 MA	I
DPT- 129	STAGING AIR I FLOW RATE	AIR	4-20 MA	I
DPT- 131	STAGING AIR II FLOW RATE	AIR	4-20 MA	I
AIT- ST	EXCESS OXYGEN	FLUE	4-20 MA	I
TE- 103	MAIN AIR TEMPERATURE	AIR	TC	I
TE- 127	PLENUM AIR TEMPERATURE	AIR	TC	I
TE-	COMBUSTOR TEMPERATURE I	FLUE	TC	I
TE-	COMBUSTOR TEMPERATURE II	FLUE	TC	I
TE-	COMBUSTOR TEMPERATURE III	FLUE	TC	I
TE-	COMBUSTOR TEMPERATURE IV	FLUE	TC	I
TE-	COMBUSTOR TEMPERATURE V	FLUE	TC	I
TE-	COMBUSTOR TEMPERATURE VI	FLUE	TC	I

(1) batch report, (2) control state history report, (3) trend reports, (4) alarm history report, (5) operator action report, (6) timed shift log reports, (7) system self-health reports, (8) emergency shutdown report, (9) start and end batch reports, (10) procedures executed report, and (11) engineer/operator user name report.

Work Station

The work station shall be the interface between the engineer or operator to the process or processes. The work station shall be usable by the process engineer developing a procedure, as well as an operator presently controlling a process or processes. The work station shall be industrially rugged. System operating software, main computer hardware, color graphics touch screen CRT, power supply, and ventilation equipment shall be housed in the work station cabinet. Additionally, communications equipment that allows the work station to communicate with multiple remote process controllers or other computers should be housed in this cabinet.

The color graphics touch screen CRT is the actual operator interface with the process or processes. The color graphics screen shall provide for multiple pictorial representations of each process being controlled. A master color code scheme shall be employed to indicate alarm conditions. Additionally, the CRT shall have color coded indicators (one for each controller) of multiple process conditions. The CRT screen shall have the capability to be used for real-time trending of measured or calculated values over an operator selected history time window.

The touch screen process indicator areas shall be able to call up preselected displays for each process controller whenever the operator touches a specific indicator area. Once viewing the selected display, the operator shall be able to touch selected areas of these displays to advance the CRT to a more detailed diagram of the process. The system shall offer the operator total ability to develop unique process diagrams as the test engineer is defining his control strategies.

The work station shall be the device the test engineer uses to define the process control strategies, tag names, event/condition tables, various state conditions, printout report functions, touch screen display diagrams, and I/O configurations. The work station CRT interface shall offer the operator the ability to take manual control of a process parameter if the test engineer has allowed for such manual control action.

The work station shall be considered as peripheral to a remote process controller or controllers. This occurs once a controller has been instructed as to control strategies of the particular process. The work station shall be able to communicate with multiple controllers. Communications shall be via isolated twisted wire pair. The work station shall be able to pass multiple procedures to a controller. Therefore, in the event of inadvertent damage to the interconnecting cable, the controller can perform many procedures in sequence until repairs can be made.

It is recommended that the control system have the actual control strategy intelligence device located as close as possible to the process itself. This device would typically be termed the controller.

Control Components

The control elements shall be the heart of the control system. All control functions shall be performed by this unit requiring no additional hardware or software including start-up, operation, and shut-down. The controller shall have the ability to implement 32 PID, PI, PD, I, P, D, error square, bias, ratio, lead/lag, or dead time control loop algorithms and carry them out in the course of an individual control strategy. The control output capability shall include a minimum of thirty-two loop control signals.

200 Analog Input Signals
500 Discrete I/O Signals

Additional channel capability to support frequency, period, and totalized data.

I/O Modules

The I/O modules are connected to their respective controller. The I/O modules shall have the capability to connect to all commonly used industrial sensors, transmitters, and preconditioned signals. The I/O structure shall provide a high degree of flexibility to be cost effective from an initial purchase and installation standpoint. The I/O modules shall have environmental temperature and selective humidity ratings so that they are suitable for mounting at the process. The system I/O shall measure each input (analog or discrete) and update each output (analog or discrete) multiple times per second.

The I/O module wire terminations shall be designed in such a way that process sensor wires do not require disconnection in order to repair or replace module electronic components. The I/O modules shall be equipped to perform run time diagnostics in conjunction with the controller.

It is urged that analog I/O resolution be 12 bits or better. The system I/O module capability shall offer the following:

Available Inputs:

Voltage (DC)	+25 MV, +100 MV, +1V, +10.0V
Currents (DC)	4- 20 MA
Thermocouples	J, K, T, E, R, S, B types -- cold junction compensation & linearization incl.
Contact Closures	Dry contact (open or closed)
RTD's	100 Ohm platinum
Discrete	30VDC, 60VDC, 120VDC, 120VAC
Pulse	0 - 65,000 counts
Serial	RS-232, IEE-488 from analyzers

Available Outputs:

Voltages (DC)	0-5V, 0-10.0V
Currents	1-5 MA, 4-20 MA
Discrete	60 VDC, 120VDC, 200VDC, 120VAC
Time Proportional	
Pulse Train	
Trigger Output or Trigger Input	
Stepper Motor Output	

Uninterruptible Power Supply (UPS)

An uninterruptible power supply shall be supplied to protect the system from undesirable system shut-down and/or loss of process control programs and data. Each process controller and its associated I/O modules shall be protected by a UPS. Upon loss of AC power to the controller or I/O module, the UPS battery backup power shall maintain the scheduled process control procedure or sequenced procedure for up to 2-1/2 hours.

Environmental

The work station shall be placed in a control room that is normally air-conditioned for personnel and instrument comfort. Nevertheless, equipment shall be rated to continue operating normally under the following environmental conditions:

Temperature	10 - 45°C
Humidity	20 - 80 percent noncondensing

The control elements an I/O modules may be located next to process equipment in equipment halls or on the outside. Minimum requirements for these components are:

Temperature	0 - 60°C
Humidity	10 - 90 percent noncondensing

Required components will be mounted in NEMA enclosures to protect them from the environment in particularly hostile areas.

The overall system main components will be subjected to routine vibration levels from the environment and process equipment operation. Positive evaluation shall be given to those systems publishing vibration specifications. Vibration specifications should be presented for all three axes (Verticle, Horizontal, Transverse). Favorable evaluation would be given to those systems meeting or exceeding the data presented below:

Work Station	5-15	Hz0.0020"
	16-33	Hz
Controller, I/O Module, and UPS	5-15	Hz0.060"
	16-25	Hz0.040"
	26-33	Hz0.020"
	34-40	Hz0.010"

3.4.7 Product Control System

Construction, operation, and evaluation of the prototype low-NO_x burner system will allow the determination of which control loops, sensors, and data are important and are essential to operate a system of this kind. It will also permit the optimization of the fuel train and various other aspects of the design. With this information, an optimum control system for the application can be specified. Microprocessor technology today provides the system designer with great flexibility at ever decreasing cost. Without the fundamental knowledge of all requirements of the system to be controlled a system can not be optimized. At this time, reduction in the scope of the proposed control system for the prototype would be speculation and may result in an inflexible system that would not be in the interest of this program. Another important aspect of the design of any product is the expected product life cycle and the number of units over which the development cost must be amortized. It appears that the number of units that could be allocated to a single supplier are in the hundreds rather than thousands. This restriction would lead to less customization than would otherwise be possible, i.e. commercially available control systems should be adapted for the application.

SECTION 4

CONCLUSIONS

The initial objective of this project was to design, fabricate, install and evaluate the EPA low-NO_x heavy oil burner for an industrial package boiler in the 59 to 74 MW (200 to 250 MMBtu/hr) thermal input range. Early in the project, this objective was revised in two ways. The capacity range for the burner was lowered and broadened because (1) almost no industrial boilers in the 59 to 74 MW range were firing residual oil to serve as a demonstration, and (2) most operators who could use the burner for low-NO_x firing of nitrated waste had boilers in the 15 to 29 MW (50 to 100 MMBtu/hr) thermal input range. The design range was accordingly changed to 15 to 59 MW (50 to 200 MMBtu/hr).

The second revision of the objective was to respond to peer review comments on the previous evaluation of the EPA burner on an enhanced oil recovery steam generator. The panel concluded that the earlier design was not appropriate for industrial boiler applications because of slow thermal response and unacceptable space requirements. Accordingly, the objective was modified to attempt to adapt the earlier design to address the peer review comments without conducting further developmental testing.

In addressing these objectives, the design development effort in the current project led to selection of the lightweight refractory precombustor/burner design with boiler sidefire air as discussed in the previous pages. Although this burner was not fabricated and evaluated in the field, the following conclusions on the design are made based on the process engineering analyses done as part of the design development.

Emissions Performance

The estimated performance of the design based on previous test results and kinetic estimates is 85 ppm at 3 percent oxygen. The emission goal selected for this program was 100 to 125 ppm, so the final design should give sufficient margin to meet the emission performance demands of the intended market.

Burner Performance

The use of the lightweight refractory should allow thermal response during startup, shutdown and load swings comparable to conventional burners and should not constrain industrial boiler applications. The burner is smaller, much lighter, and cheaper than the earlier EPA oil burner design. The control logic during start-up is more complex due to the two-stage operation, but not out of line with new boilers with advanced low-NO_x systems.

Market Niche

The burner addresses a need for both high nitrogen residual oil firing, and cofiring of nitrated wastes. Conventional low-NO_x burners for high-capacity package boilers firing high nitrogen residual oil cannot lower emissions below the 250 to 350 ppm range without causing flame impingement, combustible emissions, or instabilities. With waste cofiring, the unique hot first stage used in the burner design offers simultaneous high waste destruction efficiency and low-NO_x emissions. This burner avoids the problem with other burners where measures taken to lower NO_x are counterproductive for high waste thermal destruction.

Reliability

The present design uses lightweight refractory to improve thermal response and reduce failure risk from thermal shock. However, the design increases the risk of mechanical failure and overtemperature. The upper temperature limit on the lightweight refractory specified in the design is 1570 to 1649°C (2850 to 3000°F). The material has been extensively used in heat treating furnaces with quiescent flows at temperatures below 1540°C (2800°F). The primary concern with the present application is the turbulent, fuel rich environment with temperatures approaching 1570°C (2850°F). The subscale endurance tests of the material done in the present program showed little materials degradation for the design temperature tests. The overtemperature failure mode tests where temperatures were deliberately run above 1570°C (2850°F) showed some destruction of the "Unikote S" surface spray coating. The refractory manufacturer says this coating is applied to give the new refractory surface rigidity prior to curing. Once the refractory is hardened by curing, the surface coating is no longer needed. The surface conditions of the refractory should obviously be monitored closely in the first prototype demonstration of the burner. In a commercial field installation not related to the present program, lightweight refractory similar to the cylindrical section of the present design has performed well in the cylindrical section of an enhanced oil recovery steamer for over 6 months of operation.

Scale-Up

Burner design data are given over a 4:1 capacity range. The general configuration, stoichiometric ratios, residence times and temperatures all remain nearly identical across that range, however. Therefore, there is not expected to be significant performance variations with scale-up.

Developmental Status

Although the burner concept is derived from the earlier EPA oil burner, there are numerous differences in materials and configuration that were made to address the industrial boiler market. These changes were reviewed by an industrial peer review panel in November 1986, which concluded the design changes were logical to meet the industrial boiler application objectives. Nevertheless, optimization testing is needed for the distribution of stage air and the fuel/air control sequence during startup, shutdown, and load following. Thus, the first prototype field evaluation will have a larger component of shakedown and confirmatory testing than would be the case for a simple hardware scale-up.

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ABBREVIATIONS

CAA	Clean Air Act
CAD	Computer aided design
DRE	Destruction and removal efficiency for waste thermal destruction
EOR	Enhanced oil recovery system generator
FR	Firing rate, thermal input
MW	Thermal input in megawatts
MMBtu/hr	Thermal input in million Btu per hour
NEDS	National Emission Data System
ng/J	Emission factor, nanograms pollutant per Joule fired
NO_x	Oxides of nitrogen, nitric oxide (NO) and nitrogen dioxide (NO_2)
NSPS	New Source Performance Standards
OAQPS	EPA Office of Air Quality Planning and Standards
PBS	Package boiler simulator
PIC	Products of incomplete combustion
ppm	Species concentration in parts per million by volume
RCRA	Resource Conservation and Recovery Act
SR	Stoichiometric ratio. Ratio of actual to theoretical air
TFN	Total fired nitrogen

APPENDIX A

SITE SELECTION

A.1 APPROACH

The site selection process was to have been an eight step sequence as outlined below. Prior to truncation of the project scope because of funding limitations, five candidate sites had been identified through Step 5 and one candidate through Step 7. The one candidate site that proceeded through Step 7 eventually declined to participate after a high level management review within the company. Site visits were planned for the other five candidates prior to the curtailment of the site selection process.

The site selection process was initiated by first outlining the specifications of the boiler at a potential host site . These specifications initially included a firing capacity in the range of 59 to 73 MW (200 to 250 MMBtu/hr) and are summarized in Table A-1. As it became obvious that the number of candidate boilers that met these specifications, particularly the firing capacity, were very limited, the specifications were broadened to include firing capacities as low as 36 MW (125 MMBtu/hr). In either case the following procedure was followed in obtaining a potential host site.

1. Obtain lists of potential boiler sites (sources will be identified later)
2. Make initial telephone contact with company to determine:
   - If boiler was operable and able to run on heavy fuel
   - If there was an interest in the program
   - Responsible individuals to decide availability of site and interest of the company
3. If interest expressed in "2", send letter to responsible individual
4. Followup telephone call to answer questions, check progress, and level of interest
5. Screen candidates for possible site visits
6. Make site visit, discuss with responsible parties
7. Screen candidates and make a formal request
8. Enter into a formal agreement with host site

The approach and progress in each of these steps is outlined in the following sections.

TABLE A-1. SITE SELECTION CRITERIA

Packaged boiler -- 2 drum D-type
Single burner No. 6 oil/gas (high N oil)
59 to 73 MW thermal input (200 to 250 MMBtu/hr)
Air preheat or economizer
Spare capacity and schedule flexibility
High nitrogen waste generation
NO_x problem or interest in control technology
Existing Coen burner and controls
Space available and accessible for retrofit
Continuous steam demand
Well instrumented
Skilled operators/maintenance staff
Willingness of host site
Proximity to Acurex and Coen

A.1.1 Site Lists

Lists of potential sites were obtained from the following sources:

- Industry trade groups
- Air pollution regulatory agencies (local, state, federal)
- National Emissions Data System (NEDS)
- California Air Resources Board boiler data (RAMOFF)
- Chemical companies with potential of having nitrated wastes
- Babcock & Wilcox large package boiler sales lists
- Retrofit burner manufacturers installation lists
- Radian Report on Boiler Installations (from Power Magazine)
- Army headquarters
- Navy headquarters
- Air Force headquarters
- Miscellaneous government sources
  - DOD
  - DOE
  - NASA
  - GSA
  - U.S. Post Office
  - Veterans Administration
  - EPA Federal Facility Coordinator

A brief comment on the effectiveness of each of these sources is given in the sections that follow.

A.1.2 Industry Trade Groups

Table A-2 lists the industrial trade groups that were contacted. The industrial trade groups did not generally supply additional leads beyond those received from the independant contacts with their constituent members.

A.1.3 Air Pollution Regulatory Agencies

Table A-3 lists those air pollution regulatory agencies that were contacted. Because many districts do not have NO_x control regulations on old boilers of this size, they often were either not aware of boilers firing No. 6 oil or were not aware of any that had a NO_x control problem. A few districts were quite helpful in providing what information they had on boilers in the size range of interest.

It was hoped that the air pollution agencies could provide leads to an oil fired boiler that was having trouble meeting NO_x regulations. However, this did not occur due to three reasons: (1) lack of NO_x regulations for boilers; (2) few single burner package boilers in this size range; and (3) very low current firing of No. 6 oil as a boiler fuel. However, if further site selection is required, it is recommended that further contacts be made with air pollution control agencies. Contacts should be focused in those regions which are in nonattainment for ozone or NO_x and/or where No. 6 fuel oil is most likely to be utilized. Such regions could include the Southeast (Texas, Louisiana) or the Northeast (New England) where a high percentage of fuel oil is consumed.

TABLE A-2. INDUSTRY TRADE ASSOCIATION CONTACTS

Organization	Location	Contact
Western Oil and Gas Association	Seattle, WA	D. Vogelquist
Assoc. of Washington Business	Seattle, WA	R. Van Gohren
Oil Heat Inst. of Washington	Seattle, WA	E. Bishop
Northwest Pulp & Paper Assoc.	Seattle, WA	L. Rust
American Boiler Manufacturers Association	Arlington, VA	W. Axtman
Council of Industrial Boiler Operators	Burke, VA	W. Marx
Texas Chemical Council	Austin, TX	J. Fisher
Texas Mid Cont. Oil & Gas Association	Austin, TX	B. Landerbeck
American Petroleum Industry	Washington, DC	E. Crockette
Chemical Manufacturers Assoc.	Washington, DC	P. Duff
Southern California Gas	Los Angeles, CA	J. Gardetta
Gas Research Institute	Chicago, IL	R. Kurzynske

TABLE A-3. AIR POLLUTION REGULATORY AGENCY CONTACTS

Organization	Location	Contact
Puget Sound APCD	Seattle, WA	F. Austin
Texas Air Control Board	Houston, TX	S. Keil
EPA Region 9	San Francisco, CA	C. Seeley
State of Florida Dept. of Environmental Region	Tallahassee, FL	S. Suec
NY Dept. of Environment	Albany, NY	R. Warland
NY Dept. of Environment	Warreburg, NY	M. Delawater
Bay Area APCD	San Francisco, CA	S. Hill
NJ Bureau of Air Pollution Control	Trenton, NJ	W. O'Sullivan
Penn. Bureau of Air Quality Control	Harrisburg, PA	J. Walker
Kern County APCD	Bakersfield, CA	
California Air Resources Board	Sacramento, CA	R. Menebroker
Connecticut Department Environmental Prot.	Hartford, CT	J.Royce
South Coast AQMD	El Monte, CA	M. Cruz
Ventura APCD	Ventura, CA	C. Kraufe
San Diego APCD	San Diego, CA	J. Lake

A.1.4 National Emissions Data System (NEDS)

Early in the site selection process the EPA was contacted to provide a listing of residual oil-fired boilers in two size groups: 53 to 73 MW heat input (180 to 250 MMBtu/hr) and 30 to 53 MW heat input (100 to 180 MMBtu/hr). These listing are organized alphabetically by state, then by county, and finally by company. Although this file is constantly being updated, it is not a comprehensive listing. It was found that many of the contacts made through these listing were:

- No longer firing oil
- Multiple burner and/or field erected boilers
- No longer operational
- Had capability to fire oil at one time but were firing other fuels

The listings were prioritized by first contacting those companies that might also be producing a highly nitrated waste, might be under a regulatory constraint (California, Texas, Louisiana, New Jersey, New York, and Pennsylvania), or might have a higher probability of using No. 6 fuel oil (Northeast, South, or Northwest). It was also soon found that may of the large boilers listed in the pulp and paper industry had the capability to fire oil but were often wood or wood chip fired stokers and not packaged boilers. Therefore, the pulp and paper industry received a lower priority than others such as the chemical industry.

These lists were also compared to other sources used in the site survey process to compliment or verify the NEDS data. Primarily, the NEDS data provided an initial identification of companies with boilers in the size ranges of interest.

A.1.5 California Air Resources Board (CARB)

One initial approach was to seek a site within California for two reasons: 1) Air pollution regulations are the most stringent in the nation especially with regard to NO_x; and 2) The logistics of site construction and testing would be simplified by proximity to Coen and Acurex. To identify local candidate sites, the data bank assembled by the California Air Resources Board (CARB) for the NEDS was obtained. This data bank provided more information then reported in the NEDS for California, and additional boilers were identified as candidates. Unfortunately, although many had once had the capability of firing No. 6, most were now firing natural gas due to lower costs.

A.1.6 Chemical Companies with Nitrated Waste

In 1983, EPA-Cincinnati conducted a study in which hazardous waste compounds were identified and the manufacturing process that produced these wastes were given. The compounds were categorized into several classes including one class of wastes containing nitrogen. From these lists, those chemical industries that produced a relatively high volume of waste were identified. From the Chemical Week Buying Guide Directory, companies involved in the production of candidate compounds were identified. Table A-4 lists those nitrated compounds with the associated companies involved in their manufacture. Again, cross reference to other boiler lists was attempted. In many cases, common company names were identified but it was not always known if the particular sites identified also manufactured the nitrated compounds. Several high priority sites were found through this avenue. On the whole, either the manufacturing site did not have a large boiler, or they were no longer manufacturing the compound in question, or the amount of waste had been minimized through recent waste recycle/reuse refinements in the manufacturing process.

TABLE A-4. NITRATED COMPOUND MANUFACTURERS

Nitrobenzene

Allied Chemical
Dupont
First Chemical Corp.
Mobay Chemical Corp.
Monsanto
Rubicon Chemical Inc.
McKesson Chemical Co.

Acrylonitrile

Fallek Chemical Corp.
B. F. Goodrich Chemical Co. Div.
Dupont
Monsanto
Vistron Corp. (Std Oil Co of Ohio)
ICC

Pyridines

Union Carbide, Danbury, CT
Koppers Co. (Chemical) Pittsburgh, PA
Nepara Chemical Co. Inc.
Reiley Tar Chemical Corp.

Aniline

Air Products and Chemicals
American Cyanamid Co. (Organic Chem Div)
Dupont
First Chemical Corp.
Mobay Chemical Corp.
Uniroyal

Allcylamines

Air Products and Chemicals
ARMAK and Chem. Div.
Ashland Chem. Co.
BASF Wyandotte Corp.
Ethyl Corp Int'l Chem. Div.
Hess, John R. and Sons
Mars Chemical Corp.
Onyx Chem. Co.
Union Carbide, Chemicals and Plastics

(continued)

TABLE A-4. (continued)

Diphenylamine (DPA)

Smith, i.g., Frederick Chem. Co.
American Cyanamid
McKesson Chemical Co.
Mobay Chemical Corp.
Uniroyal Inc.

Diphenylmethane Dissoyante

Mobay Chemical Corp.
Rubicon Chemical Inc.
Upjohn Co. (the Polymer Chem. Div.)

Carbamate Pesticides Carbaryl

Agrico Chem. Co.
Alpha International Chemical Inc.
Ashland Chem. Co. (Ind'l Chems and Solvents Div.)
Baker, J. T.
Captree Chemical Co.
Harshaw Chem Col.
Intsel Corp.
Mineral Resources and Development Corp.
Philipp Brothers Chemical Inc.

Urea

Ashland Chemical Co.
Borden Chem. Div. of Borden
Columbia Nitrogen Corp.
ICC Industries Inc.
McKesson Chem. Co.
Olin Corp, Stanford, CT
Stinner Oil and Chemical
Thompson-Howard Chem. Co.
Union Chemicals Div. of Unocal
Vistron, Cleveland, Ohio

(continued)

TABLE A-4. (continued)

Rubber Industrial Wastes (Nitrobenzene)

Cities Service Co, Columbia Chem. Div. Tennessee Chem. Co.
Dow Corning Corp.
Dupont
Exxon Chem. Co., Houston, Texas
Firestone Synthetic Rubber and Latex Co., Akron, Ohio
B. F. Goodrich, Chem. Group
Thiokol Corp. Ordnance
Uniroyal
U.S. Industrial Chem.

Toluene-2-4 Diamine

Air Products and Chemicals
Olin Corp.

Dinitrotoluene

Air Products and Chemicals
Dupont

Dinitrophenols (Dyestuff intermediate)

Blue Spruce Co.

Atrazine

Ciba-Geigy Corp.

Hydrazine

A&S Corp.
Aceto Chem. Co.
Fairmont Chem. Co.
Hummel Chem. Co.
ICC Industries Inc.
Mobay Chemical Corp.

A.1.7 Babcock and Wilcox Boiler Lists

Early in the search for a site, two Babcok and Wilcox boiler designs produced in the late sixties and early seventies were explored as candidates for the low-NO_x burner retrofit. One design, known as an FM boiler, has a single, large burner and a relatively large firebox. This design was produced for capacities up to 114,000 kg/hr (250,000 lbs/hr) of steam. Fourteen sites were initially identified for this design. The second design produced in the early sixties is the cyclopac boiler which has a removable oil-fired cyclone burner mounted on one end of the boiler. This design is also ideal for retrofit with the low NO_x burner design since the original burner was fairly large as well. Nine cyclopac boiler sites were initially identified but none were still in service.

If further site selection is required it is recommended that the other major package boiler manufacturers (CE, Foster Wheeler, Riley Stoker) be contacted for similar lists.

A.1.8 Retrofit Burner Manufacturer Lists

A major burner retrofit manufacturer was able to provide the project with a list of sites which had made a burner conversion within the past 15 years. Only those sites were selected that had the capability of burning fuel oil and were within the capacity range of interest. Initially this capacity range was from 64,000 to 89,000 kg/hr (140,000 to 195,000 lb/hr) of steam but a second list was generated in the range of 55,000 to 68,000 kg/hr (120,000 to 150,000 lb/hr) of steam. The first list consisted of 107 sites of which all were contacted. The second screening produced about 140 potential sites of which most were contacted prior to cessation of this activity. Many of the sites in the second listing however were at the same companies as the first list. These lists proved to be the most useful information source of any of the sources reviewed. In most cases the data on the boiler was reliable and a contact was provided at the company.

A.1.9 Radian Report

The EPA Project Officer provided a list of boilers compiled from sales information presented in Power Magazine dating from 1974. This list included 24 boilers in the size range and fuel of interest. The fuels were listed as oil, oil and gas, or No. 6 oil. It was not specified if those listed as oil were heavy or light oil-fired. However, most of these listings were duplicates of information provided from other sources.

A.1.10 Navy

The Navy has many boilers associated with its shipyards. It also generates considerable nitrated waste in the form of specialized torpedo motor fuel. Thus it seemed that the Navy would be a natural host site for this project. The primary source of information was the Navy Energy and Environmental Support Activity, NEESA, located at Port Hueneme, California. The energy office maintains information on the size and fuel use all the Navy boilers. The environmental office oversees research on the overall environmental problems in the Navy and in particular disposal of hazardous waste.

Initial discussion with personnel in the energy office revealed a few boilers in the size range of interest (52 to 73 MW) (180 - 250 MMBtu/hr input). In response to a letter explaining the program and requesting participation, NEESA took the position that they could not participate in the program due to legal problems associated with liability for storage, transportation and burning of hazardous waste. Simultaneously with the inquiry, a number of other Navy contacts were made including the following:

- Naval Surface Weapons Center, Dahlgren, VA (Hazardous Waste Research)
- Naval Facilities Engineering Command, Washington, DC
- Naval Facilities Engineering Command, Philadelphia, PA
- Philadelphia Naval Shipyard
- Naval Ordnance Station, Indian Head, Maryland
- Puget Sound Naval Shipyards, Seattle, Washington
- U.S. Navy Base, Keyport, Washington

None of these contacts led to a promising site and usually the contact directed the inquiry to Washington which in turn directed it back to NEESA at Port Hueneme. Thus, further inquiries with the Navy were terminated.

A.1.11 Army

The Army maintains boilers at a number of their bases and generates some nitrated waste from the production of munitions. The following organizations and/or sites were contacted:

- Construction Engineering Research Lab (CERL), U.S. Army, Champaign, IL (Boiler Lists)
- Holsten Ammunition Plan, Kingsport, TN
- Test and Evaluation Command (TECOM), Aberdeen Proving Ground, MD
- Rock Island Arsenal, Rock Island, IL
- Picatinny Arsenal, Dover, NJ
- Fort Lewis, Seattle, WA
- Army Material Command Headquarters, Alexandria, VA
- Toxic and Hazardous Material Agency, U.S. Army Aberdeen, MD
- Army Environmental Hygiene Agency (AEHA) MD

Most of the boilers found on Army bases were used for space heating with capacities less than 18,000 kg/hr (40,000 lb/hr) of steam.

The few large boilers associated with munitions production were either coal-fired or no longer in service. This avenue of inquiry was therefore discontinued.

A.1.12 Air Force

The Air Force also generates a nitrated waste in the form of hydrazine and operates boilers at most of its bases. It also has a coordinated environmental hazardous waste program. The Air Force maintains its inventory and coordinates its hazardous program from Tyndall Air Force Base in Florida. A solicitation letter was sent to the hazardous waste coordinator but because of lack of funds and no boilers in the size range of interest they declined to participate in the program. A few individual bases were contacted including:

- Air Force Rocket Propulsion Lab, Edwards Air Force Base, CA
- Vandenberg Air Force Base, Santa Maria, CA
- McCord Air Force Base, Tacoma, WA
- Wright Patterson Air Force Base, Dayton, O

Currently the hydrazine from the rocket fuel is shipped off site for disposal. Typical boiler sizes were in the range of 23,000 to 27,000 kg/hr of steam (50,000 to 60,000 lb/hr of steam). No promising site were found and this avenue of inquiry was terminated.

A.1.13 Miscellaneous Government Sources

Other government sources that were contacted included the following:

- NASA
- Department of Energy, Washington, DC
- Tennessee Valley Authority, TN
- U.S. Post Office, Washington, DC
- Veterans Administration
- Defense Utilization and Marketing Service, Environmental Protection Department, Tech Support Division, DOD, Battle Creek, MI
- General Services Administration, Energy Coordinator, Washington, DC
- Environmental Protection Agency, Federal Facilities Coordinator
- Department of Defense, Defense Environmental Leadership Group, Washington, DC

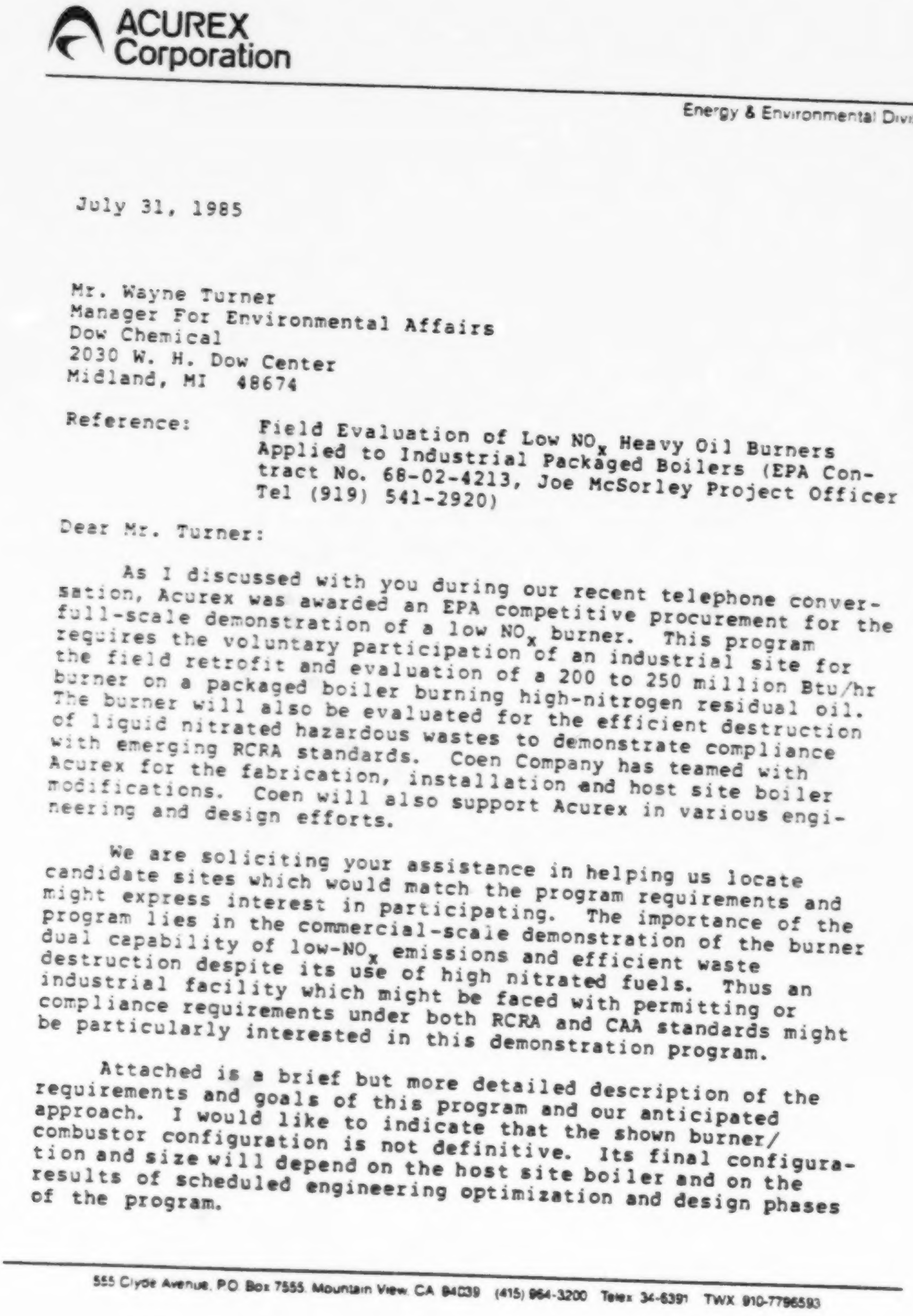
The latter three were very helpful in providing contacts at the Army, Air Force, Navy, TVA, DOE, Post Office, and Veterans Administration. Unfortunately, none of these leads resulted in a high priority site. The DOD Defense Environmental Leadership Group provided numerous contacts within the military and seemed to be genuinely interested in the program. However, contacts within those organizations would often refer back to the Defense Environmental Leadership Group. Thus, this avenue was also terminated in favor of finding a higher probability private sector industrial site.

A.1.14 Contacts

As the site lists were developed, an attempt was made to prioritize the potential site for an initial telephone contact. High priority sites included those that might also have a nitrated waste problem, a NO_x regulatory problem, or had a high probability of using a No. 6 fuel oil. Sites located on the West Coast also were given a higher priority.

The initial strategy was to make a telephone contact with the person responsible for environmental affairs. Questions on the characteristics of the boiler were often directed to the person responsible for the operation of the boiler. If the boiler characteristics met the required specification (or nearly met them) and there was an interest expressed, this telephone call would be followed up by a letter explaining the program and requesting their interest in participation. A sample copy of this letter is shown in Figure A-1. Figure A-2 shows a more detailed description of the program which was also sent to most contacts. The incentives cited to encourage participation included the following:

- Potential to meet and exceed any NO_x regulatory requirements
- Ability to dispose of nitrated waste compounds
- A new burner and control system at no cost to the host site
- Return of the boiler to its original condition at the end of the project if so desired
- Public relations benefit for controlling emissions



ACUREX
Corporation

Energy & Environmental Division

July 31, 1985

Mr. Wayne Turner
Manager For Environmental Affairs
Dow Chemical
2030 W. H. Dow Center
Midland, MI 48674

Reference: Field Evaluation of Low NO_x Heavy Oil Burners Applied to Industrial Packaged Boilers (EPA Contract No. 68-02-4213, Joe McSorley Project Officer Tel (919) 541-2920)

Dear Mr. Turner:

As I discussed with you during our recent telephone conversation, Acurex was awarded an EPA competitive procurement for the full-scale demonstration of a low NO_x burner. This program requires the voluntary participation of an industrial site for the field retrofit and evaluation of a 200 to 250 million Btu/hr burner on a packaged boiler burning high-nitrogen residual oil. The burner will also be evaluated for the efficient destruction of liquid nitrated hazardous wastes to demonstrate compliance with emerging RCRA standards. Coen Company has teamed with Acurex for the fabrication, installation and host site boiler modifications. Coen will also support Acurex in various engineering and design efforts.

We are soliciting your assistance in helping us locate candidate sites which would match the program requirements and might express interest in participating. The importance of the program lies in the commercial-scale demonstration of the burner dual capability of low-NO_x emissions and efficient waste destruction despite its use of high nitrated fuels. Thus an industrial facility which might be faced with permitting or compliance requirements under both RCRA and CAA standards might be particularly interested in this demonstration program.

Attached is a brief but more detailed description of the requirements and goals of this program and our anticipated approach. I would like to indicate that the shown burner/combustor configuration is not definitive. Its final configuration and size will depend on the host site boiler and on the results of scheduled engineering optimization and design phases of the program.

555 Clyde Avenue, P.O. Box 7555, Mountain View, CA 94039 (415) 964-3200 Telex 34-6391 TWX 910-7796593

Figure A-1. Sample letter sent to industrial contacts.

We look forward to your support in locating candidate sites. Your suggestions and ideas will be most gratefully appreciated and definitely a vital contribution to this program.

Sincerely,

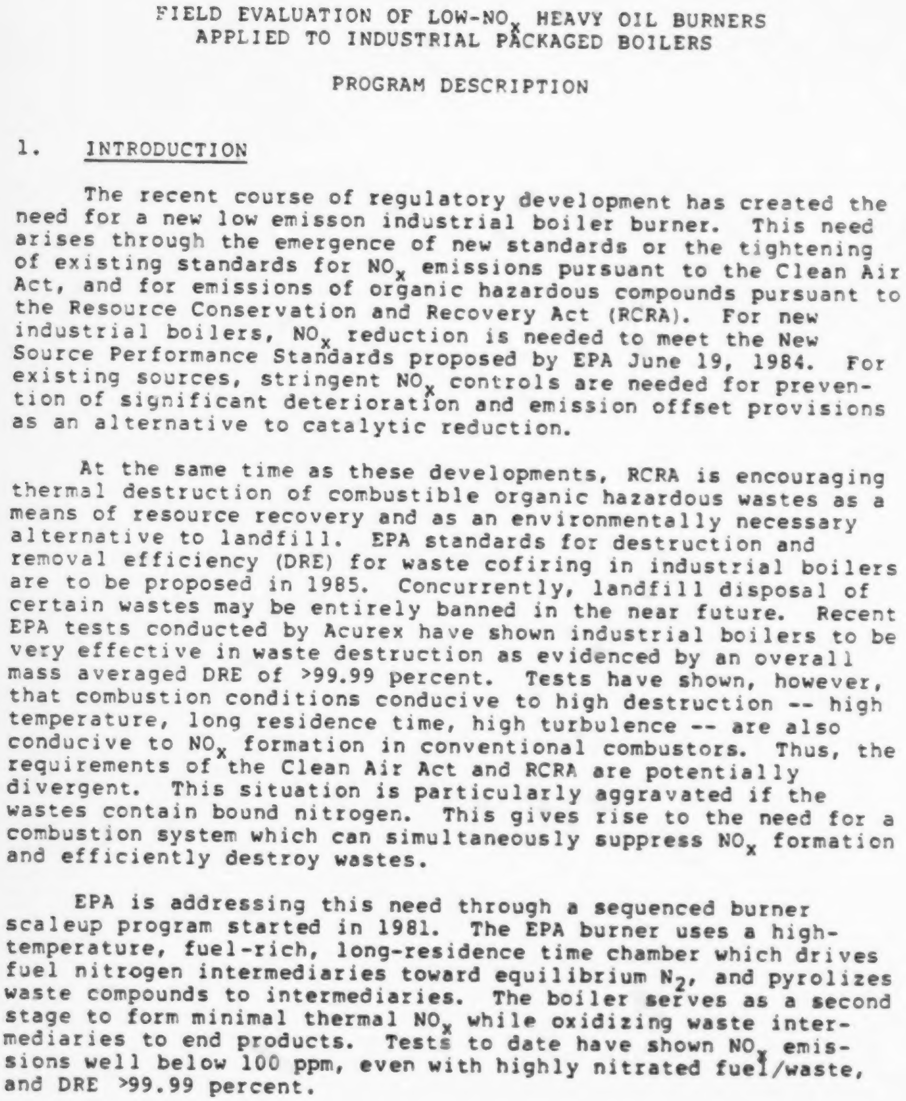
Rick Brown

Richard A. Brown
Manager, Combustion Laboratory

RAB/sla

Encls.

Figure A-1. (continued).



FIELD EVALUATION OF LOW-NO_x HEAVY OIL BURNERS APPLIED TO INDUSTRIAL PACKAGED BOILERS

PROGRAM DESCRIPTION

1. INTRODUCTION

The recent course of regulatory development has created the need for a new low emisson industrial boiler burner. This need arises through the emergence of new standards or the tightening of existing standards for NO_x emissions pursuant to the Clean Air Act, and for emissions of organic hazardous compounds pursuant to the Resource Conservation and Recovery Act (RCRA). For new industrial boilers, NO_x reduction is needed to meet the New Source Performance Standards proposed by EPA June 19, 1984. For existing sources, stringent NO_x controls are needed for prevention of significant deterioration and emission offset provisions as an alternative to catalytic reduction.

At the same time as these developments, RCRA is encouraging thermal destruction of combustible organic hazardous wastes as a means of resource recovery and as an environmentally necessary alternative to landfill. EPA standards for destruction and removal efficiency (DRE) for waste cofiring in industrial boilers are to be proposed in 1985. Concurrently, landfill disposal of certain wastes may be entirely banned in the near future. Recent EPA tests conducted by Acurex have shown industrial boilers to be very effective in waste destruction as evidenced by an overall mass averaged DRE of >99.99 percent. Tests have shown, however, that combustion conditions conducive to high destruction -- high temperature, long residence time, high turbulence -- are also conducive to NO_x formation in conventional combustors. Thus, the requirements of the Clean Air Act and RCRA are potentially divergent. This situation is particularly aggravated if the wastes contain bound nitrogen. This gives rise to the need for a combustion system which can simultaneously suppress NO_x formation and efficiently destroy wastes.

EPA is addressing this need through a sequenced burner scaleup program started in 1981. The EPA burner uses a high-temperature, fuel-rich, long-residence time chamber which drives fuel nitrogen intermediaries toward equilibrium N_2, and pyrolizes waste compounds to intermediaries. The boiler serves as a second stage to form minimal thermal NO_x while oxidizing waste intermediaries to end products. Tests to date have shown NO_x emissions well below 100 ppm, even with highly nitrated fuel/waste, and DRE >99.99 percent.

Figure A-2. **Field evaluation of low-NO_x heavy oil burners applied to industrial packaged boilers.**

At this juncture, the burner has been scaled-up to 55 million Btu/hr on a thermally enhanced oil recovery (TEOR) steamer firing an 0.8 percent nitrogen crude oil. The performance of the burner was successfully demonstrated by achieving NO_x levels of 70 ppm (versus 300 ppm for a conventional burner) with low smoke and CO emissions and satisfactory thermal efficiency. Accordingly, the next logical step is to scaleup through the size range used for most industrial boilers, particularly those cofiring hazardous wastes.

2. OBJECTIVES

The objective of the proposed program is to scaleup, fabricate, and demonstrate a 150 to 250 million Btu/hr burner on a package boiler. This size range is appropriate as it represents the upper end of the majority of oil-fired industrial boilers, particularly those in the chemical industry cofiring wastes. A package boiler is specified as it presents the sternest challenge to NO_x control and waste destruction with its tight firebox, high combustion intensity, and short residence time. The goals of the demonstration are NO_x 100 ppm (at 3 percent O_2), CO 35 ppm, smoke number 4, and operational flexibility and reliability acceptable to potential users.

3. TECHNICAL APPROACH

The program, spanning a period of 3 years, will be conducted by the Acurex Corporation with assistance from the Coen Company during design, fabrication and boiler retrofit phases. Coen Company will bring the necessary experience, credibility and realism particularly in the burner design, boiler integration and system control to ensure industry acceptance.

The technical approach is segmented in the following seven phases:

1. Industrial Boiler Site Selection
2. Burner Design and Construction
3. Installation and Startup
4. Optimization and Evaluation
5. Destruction of Industrial Waste Tests
6. Restoration
7. Coordination

The following subsection briefly describes the work and objectives in each of these phases.

Figure A-2. (continued).

3.1 Site Selection

The selection of an industrial packaged boiler for retrofit and field validation of the low-NO_x burner is an important task in this program because of decisive implication on ease and cost of retrofit and restoration. In general, the selection will be based on the following required or desirable site and boiler characteristics:

Site

- Spare capacity
- Space availability
- Continuous steam demand
- High nitrogen liquid waste availability
- Permit application status

Boiler

- 150-250 Million Btu/hr nominal capacity
- Packaged design
- High nitrogen fuel oil firing (primary fuel)
- Compatible burner configuration (single burner)
- Compatible furnace design ("D" type preferred)

3.2 Burner Design and Construction

The preliminary burner design will be based on the scaleup of the existing 55 million Btu/hr burner. An illusration of this preliminary design retrofit to the industrial boiler is shown in Figure 1. The combustor is shown in the horizontal position in line with steam generator. The combustor will use the regeneration concept previously used on the TEOR retrofit project. The key elements of this design are:

- State-of-the-art Coen SAZ/DAZ burner register technology for efficient air-fuel mixing and flame shape
- Coen MV steam atomized oil gun for efficient atomization
- Dual fuel capability with Coen natural gas spuds for boiler operation on natural gas during preheating of combustor
- Standard carbon steel material for burner and windbox with typical temperature limitations to 550°F
- Regenerative combustor design utilizing dual shell arrangement with approximate outside diameter of 11 ft
- Insulated outer shell for outside surface temperatures below 100°F
- Primary air bypass vent controlled to retain high velocity over the inner shell during low loads
- Inner refractory lined shell made of high temperature carbon steel. Prefired high-alumina (90 percent) kiln bricks for low conductivity and stress resistant properties over high temperature gradients.

Figure A-2. (continued).

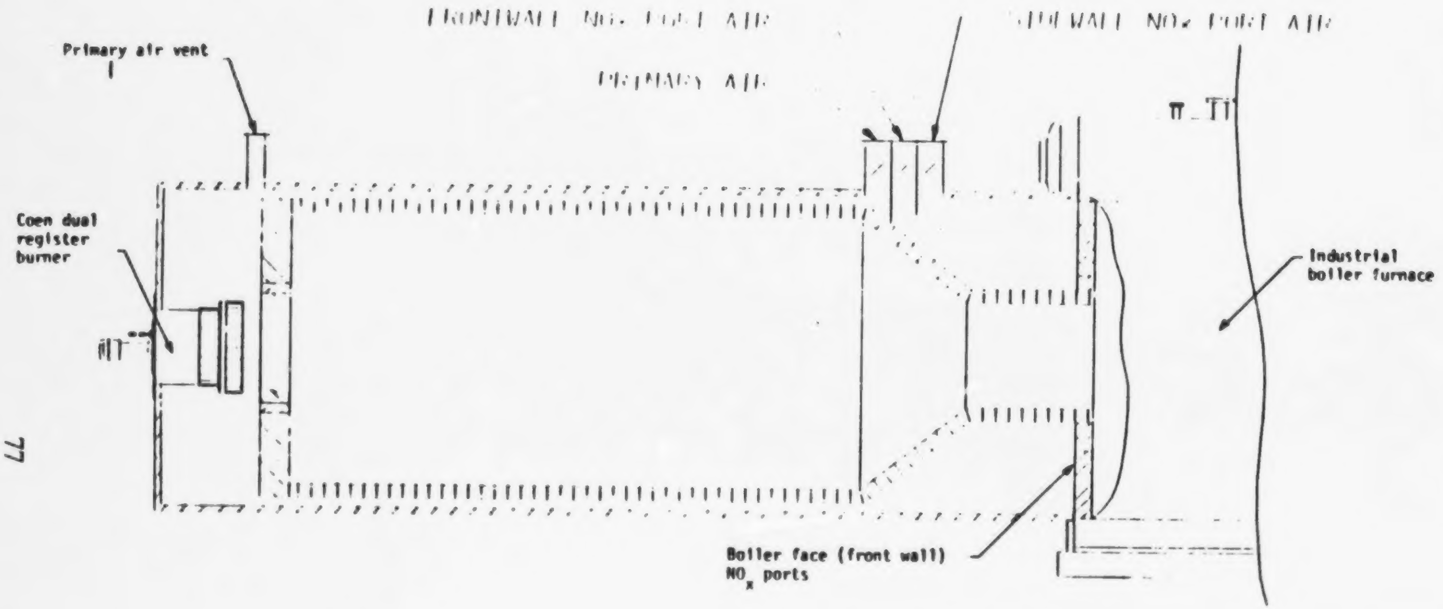

FRONTWALL NOx PORT AIR
SIDEWALL NOx PORT AIR
Primary air vent
PRIMARY AIR
Coen dual register burner
Industrial boiler furnace
Boiler face (front wall) NO$_x$ ports

Figure A-2. (continued).

- Primary air inlet with controlled vanes to partition air to the burner and secondary NO_x ports
- Combustor transition (interface) and choke area (approximately 4 ft diameter) designed for optimal furnace view angle and boiler retrofit requirements. Both transition and choke areas are brick lined as in the main combustor.
- Frontwall NO_x ports designed for slow air-gas mixing required for low NO_x
- Boiler furnace sidefire air ports and associated ducting for rapid and complete mixing to ensure low-CO/smoke emissions

The burner will be equipped with Coen controls to monitor and set air flow for optimum stoichiometry and varying steam loads, primary air vent, burner register positioning, oil viscosity (temperature) control, front- and sidefire air injection, and total overall excess air. The controls will utilize Coen proprietary and state-of-the-art microprocessor software to provide optimum load following capability without increase in smoke or CO emissions. Coen Company will fabricate the burner and controls at its Burlingame facility for shipment to the site. The design and construction of the burner is anticpated to take 12 months.

3.3 Installation and Startup

The installation and startup of the combustion system will be performed by a team of Acurex, Coen, and a general contractor. This phase of the program estimated to span 5 months will require boiler and site modifications to retrofit the burner and combustor system. Coen will also modify the existing burner control system for compatibility with the low-NO_x system. The startup and checkout phase will include preliminary cold flow checks prior to lightoff. Coen will provide a detailed lightoff sequence and check procedure. Low fire combustor refractory curing will be necessary prior to full load operation.

3.4 Optimization and Field Evaluation

Following the burner startup and checkout tests, the facility will be subjected to a 2 month detailed optimization test and 1 month performance evaluation program. The objective of the optimization tests is to determine the operational settings of the burner for minimum NO_x, CO, and smoke over a wide range of boiler loads. Thermal and mechanical performance will also be optimized.

Figure A-2. (continued).

The following primary variables effecting the emission performance of the burner will be investigated during optimization tests:

- Burner
  -- Fuel atomization (pressure, temperature)
  -- Mixing (register air swirl)
  -- Firing rate (oil/air flow)
- First stage combustor zone
  -- Stoichiometry (typically 0.6 - 0.65 required)
  -- Temperature (combustor air preheat)
  -- Residence time (burner load, air flow, temperature)
- Second stage injection rate and location
  -- Air distribution (choke versus boiler sidefire)
  -- Overall excess air (boiler exit)

The objective of the long-term (30 day) emission evaluation performance tests is to measure burner thermal performance and emissions under typical plant operation.

3.5 Destruction of Industrial Wastes Tests

Emission tests will be performed to evaluate the destruction and removal efficiency (DRE) and PIC emissions during cofiring with nitrated wastes. The tests will be similar to those performed for the industrial boiler hazardous waste cofiring for the EPA HWERL in Cincinnati. Liquid nitrated wastes containing acrylonitrile, nitrobenzene, aniline or pyridine will be considered for the test program. If nitrated wastes are not available at the selected site, spiking of the available liquid waste with a combination of these organic compounds will be considered for these tests.

3.6 Restoration

Following the completion of the validation and performance tests the host boiler and facility will be restored to original conditions unless alternate arrangements are negotiated between the EPA and the host site. Auxiliary systems such as burner controls, combustion air fan, secondary air ports, etc. may remain if the host site agrees.

Figure A-2. (continued).

3.7 Coordination

The program will utilize a technical advisory panel to monitor and provide feedback on the plans, progress and results of each phase on a routine basis. The panel will be selected in consultation with EPA from among all groups interested in the development or implementation of the technology. Suggested candidate groups are:

- User industries
  - Host site
  - CMA boiler committee chairman
- Boiler industry
  - CIBO
  - ABMA
  - Burner/boiler manufacturer
- R&D groups
  - EPA research laboratory
  - EPA/DOE contractors
- Regulatory groups
  - EPA, OAQPS, OSW, regional office

CC/RAB/sla

Figure A-2. (continued).

In return for these benefits the host would be required to:

- Make space available to position the new burner/precombustor
- Allow sufficient downtime to modify the boiler
- Allow the boiler to be operated through a series of test conditions both before and after the retrofit
- Provide a coordinator from the plant to interact with the EPA and its contractors. This coordinator would also sit on the Technical Advisory Panel to review design, construction plans, test plans, and final data
- Provide fuel to run the boiler during the test program (not over and above current fuel use)
- Provide normal boiler maintenance and operators
- Allow the burner to be operated 6 months after the initial test program

Within a week or so after the potential host site had received the information letter, a followup telephone call was made to the addressees to answer any questions and to obtain an initial response. Responses included:

- Need more time to canvass boiler sizes and fuel capabilities at various plants
- Need more information (usually financial impact on the host site -- downtime, fuel costs, manpower requirements, etc.)
- Need to take to higher authority
- No interest (no boilers in size range, not burning No. 6, cannot afford downtime, no manpower)
- Interested in defining the next step

If interest was expressed, more details were obtained on the boiler type, specific site information, duty cycle, regulatory situation, and potential for burning hazardous waste. The decision procedures and level of management approval was also determined. Finally if there appeared to be sufficient mutual interest, a site visit was scheduled.

At the site visit, detailed dimensions of the boiler layout were obtained and logistics were discussed with the responsible plant personnel.

This site would then be compared to other potential sites and a decision made to issue a formal letter requesting participation. If more than one suitable site were available, a priority would be established but more than one letter could be issued at one time.

A.2 SUMMARY OF CONTACTS

In total over 300 potential sites and/or companies were contacted with regard to this program. Most of these were terminated for a variety of reasons after the initial phone call. Letters were sent to the companies listed in Table A-5 and military/government installations in Table A-6. Followup calls were made to all of these. At the time this activity was put on hold, it had been decided to expand the boiler specification to include single burner package boilers down to as low as 55,000 kg/hr (120,000 lbs/hr) of steam. This change considerably broadened the potential base for site selection and another round of contacts were being initiated. From the first round, five locations were identified for site visits. Table A-7 lists the site specifications. All of these sites had expressed an interest in a site visit by Acurex or Coen.

TABLE A-5. INDUSTRY CONTACTS

Organization	Location	Contact
Keysmuth Corp	Austin, TX	A. Askew
Celanese Chem.	Dallas, TX	A. Savage
Exxon Baton Rouge, LA	T. Sullivan	
Dupont Deepwater, NJ	A. Pagaw	
Texas Eastman	Longview, TX	J. Woolbert
Dupont Wilmington, DE	D. Smith	
Dupont Beaumont, TX	R. McClure	
Dupont La Place, LA	G. Barge	
Arco Pennsylvania, PA	D. Fitts	
St. Joseph Light and Power	St. Joseph, MO	S. Brooks
Waldorf Corp.	St. Paul, MN	G. Waterhouse
Cape Industries	Wilmington, NC	B. Gravowshi
Dow Chemical	La Porte, TX	M. Dillon
Shell Oil Seattle, WA	D. Gillet	
Longview Fiber	Seattle, WA	B. Guide
Seattle Steam Corp.	Seattle, WA	F. Marshall
Pacific Power Co.	Portland, OR	B. Missen
Freeport Sulfur	New Orleans, LA	M. Wiliconsin
Chevron Richmond, CA	P. Davis	
B. F. Goodrich	Cleveland, OH	L. Clark
Mobay Chemical	Pittsburg, PA	L. Hughes
Std. Oil of Ohio	Cleveland, OH	K. Blower
Monsanto	St. Louis, MO	G. L. Jessee
Exxon Baton Rouge, LA	E. Sales	
Union Oil	Los Angeles, CA	M. Dougherty
Air Products and Chem.	Allentown, PA	J. Spata
BASF Wyandotte	Parssippany, NJ	D. Anderson
Koppers Co.	Pittsburgh, PA	M. Urlassik
American Cyanamid	Wayne, NJ	R. Dennis
First Chemical Corp.	Pascagoula, MS	T. Kissinger
Uniroyal Middleburg, CT	J. Gulak	
Harshaw Chem. Co.	Cleveland, OH	A. Koes
Rubicon Chem	Gusmar, LA	M. Keene
Kerr McGee	Tiona, CA	M. G. Edmonsen
Allied Chemical Co.	Morristown, NJ	W. M. Reiter
Texaco USA	Houston, TX	D. H. Schmude
AMOCO Chemical	Chicago, IL	J. Huddle
Boise Cascade	Portland, OR	A. Mick
Warren Petroleum	Montebello, TX	B. Langley
Ashland Chemical	Columbus, OH	R. Sterrit
Ethyl Corp.	Baton Rouge, LA	D. Park

(continued)

TABLE A-5. (continued)

Organization	Location	Contact
Union Chemical	Los Angles, CA	F. Walters
Onyx Chem. Co.	Jersey City, NJ	J. Niermiec
Mars Chem. Corp.	Atlanta, GA	J. Newton
Shell Oil Co.	Houston, TX	G. Barrington
Crown Zellerbach	Seattle, WA	J. Walters
Texaco Chem.	Bellaire, TX	G. Edwards
International Mining & Chem.	Terra Haute, IN	M. McKee
McKesson Chem. Corp.	Fort Wayne, IN	A. Peters
U. S. Industrial Chem.	Cincinnati, OH	D. Hall
Warren Petroleum	Houston, TX	L. Reed
C&H Sugar	Crockett, CA	J. Shapak
Louisiana Pacific	Sonora, CA	E. Taylor
Weyerhauser	Seattle, WA	B. Anderson
Simpson Paper	Andersen, CA	S. Narium
Masonite Hardboard	Ukiah, CA	S. Jennings
Mobil Chem. Co	Houston, TX	P. Mullin
Union Carbide	NJ	E. Southard
Union Carbide	NJ	R. Kelley
Union Carbide	Houston, TX	J. Holliday
Dow Chemical	Midland, MI	D. Wilson
Dow Chemical	Midland, MMI	W. Turna
Thiokol	Shreveport, LA	E. Sears
Crown Zellerbach	Antioch, CA	E. Chisin
General Electric	Waterford, NY	A. North
Boeing Co.	Seattle, WA	D. Smukouski
Upjohn	Kalamazoo, MI	S. Karas
Southern California Edison	Los Angeles, CA	L. Radak
Pfizer Inc.	Groton, CT	R. Pfisterer
Uniroyal Chem.	Nantuckett, CT	D. Kogut
Vista Chem.	Westland, LA	M. Hayes
Julian Material	Geisner, LA	B. Smith
P.P.G. Industries	Pittsburg, PA	M. Samuelson
P.P.G. Industries	Lake, LA	A. Pluche
Air Products and Chem	Garbiel, LA	T. Tollwater
Pratt & Whitney	Pensacola, FL	T. Butler
Pratt & Whitney	E. Hartford, CT	A. Caldwall
Vero Beach Power Plt.	Vero B., FL	M. Mossey
Marathon Oil	Geryville, LA	B. Harmon
Gulf Power	Pensacola, FL	N. Hershbeig
Monsanto Fibers	Pensacola, FL	J. Wylie
American Cyanamid	Milton, FL	N. Sharitz

(continued)

TABLE A-5. (continued)

Organization	Location	Contact
American Cyanamid	Westwego, LA	J. Schnel
Vanderbilt Chemical	Connecticut	H. Baer
Firestone	Akron, OH	J. Larman
Goodyear Tire and Rubber	Akron, OH	J. Surklia
Dupont	Orange, TX	B. Beck
Union Carbide	S. Charleston, W. VA	D. Knudsen
Air Products and Chem.	Pasadena, TX	B. Martine
Uniroyal Chem	Nantuckett, CT	G. Arndt
Monsanto	Aniston, AL	B. Chevar
Union Carbide	Texas City, TX	R. O'Brien
Dow Chemical	Texas	J. Robertson

TABLE A-6. MILITARY AND GOVERNMENT CONTACTS

Organization	Location	Contact
EPA Fed. Facilities Coord.	Washington, DC	L. Herwig
DOD Fed Facilities Coord.	Washington, DC	P. Fink
Defense Utilization and Marketing Service -- Environ. Prot. Dept.	Battle Creek, MI	L. Daley
Navy -- Chesapeake Bay	Washington, DC	S. Buckley
Defense Envir. Leadership Grp	Washington, DC	C. Schaeffer
Dept. of Defense	Washington, DC	A. Talts
Vandenberg AFB	Santa Maria, CA	L. Mitchell
Army Command HQ	Alexandria, VA	B. Hasselkus
Air Force Rocket Prop Lab	Edwards AFB, CA	J. Marshall
U.S. Navy-NEESA	Pt. Hueneme, CA	P. Jones
U.S. Navy-NEESA	Pt. Hueneme, CA	R. Winters
U.S. Navy-Naval Ord	Indian Head, MD	T. Woo
Naval Surface Weapon Ctr	Dahlgren, VA	D. Knudsen
U.S. Air Force	Tyndall AFB, FL	S. Joshi
U.S. Army-Fort Lewis	Seattle, WA	S. Miller
U.S. Navy-Puget Sound Naval Shipyard	Seattle, WA	R. Roholt
U.S. Navy Base	Groton, CT	W. Mansfield
TVA	Tennessee	T. Swanson
U.S. Army (Cor. of Engr.)	Washington, DC	L. Keller
DOE (Energy Office)	Washington, DC	E. Tuttle
U.S. Post Office	Washington, DC	F. Delisio
Veterans Adm.	Washington, DC	J. Garg
GSA	Washington, DC	J. Facaus
U.S. Army, AMC	Alexandria, VA	Maj. Trageirer
NASA	Washington, DC	D. Apsia
DOE	Germantown, MD	C. Wetty
U.S. Army-Rock Island Arsenal	Rock Island, IL	C. Sarntdman
U.S. Army-Rock Island Arsenal	Rock Island, IL	R. Shinbori
U.S. Army-Picatinny Arsenel	Dover, NJ	P. Prahlin

TABLE A-7. BOILER SPECIFICATIONS FOR HIGH PRIORITY SITES

	Number Boilers	Boiler Manufacturer	Boiler size (lbs/hr)	No. Burners Mfg.	Type	Fuel	Waste	Contact
Consolidated Edison New York, NY	20	Foster Wheeler	150,000	2, FW	D	Oil (potential problem)	None	Dom Mormile
General Electric Selkirk, NY	2	Babcock Wilcox	150,000 (90,000 to 100,000)	1, Coen	D	Gas, oil distillate	1 burns tar	Tom Wrobleski
		Combustion Engineering	150,000	1, CE	A	Gas, oil	(Haz waste)	
Monsanto Indian Orchard, MA	1	Babcox & Wilcox	150,000	1, Coen	D	Gas, oil waste (not nitrated)	Nonchlorinated	GeorgeLemos
Monsanto Fayetteville, NC	2		175,000	1, Coen		Oil	Possible NH3 waste	Phil Pruette
Tri Valley Stockton, CA	4	Nebraska	125,000	1, Coen	D	Gas, oil (.6N)	None	H. Griffiths
	1	Nebraska	100,000	1, Coen	D			
	1	Nebraska	150,000	1, Low-NO_x Peabody	D			

Telephone discussion were continuing with 12 additional sites. An additional group of over 100 remained on the list to be contacted with boilers in the smaller size range. In addition, plans were underway to scan the list of companies already contacted to determine if boilers in the range of 55,000 to 82,000 kg/hr (120,000 to 180,000 lbs/hr) of steam might be available.

APPENDIX B

SUBSCALE REFRACTORY ENDURANCE TESTS[1]

B.1 INTRODUCTION

This appendix summarizes a test series run to obtain endurance data for the lightweight refractory section at combustion conditions simulating the design conditions of the full scale burner. Three test phases were run. Initially, a nominal four week steady exposure test was run to obtain durability data. This was followed by a one week thermal transient test which tested the ability of the refractory to adapt to temperature ramps representative of industrial boiler load swings and start ups. The third phase consisted of another 4 days of steady state testing at temperatures beyond the range for which the refractory was designed. Since the testing was focused on materials durability, the primary test data was materials examination after each phase of testing and monitoring of outer shell temperatures to detect any change in thermal conductivity or heat shorts caused by refractory cracking. With this type of refractory, the failure modes of concern are weakening of surface strength and increased friability caused by overtemperature, and propagation of surface cracks in the Saffil coating caused by thermal stresses. Due to the limitations of the sub-scale system, the test conditions which most closely simulate full-scale materials performance cannot be simultaneously run with the conditions simulating full scale NO_x performance. Therefore, the NO_x emission results are not representative of the performance potential of the design.

B.2 FACILITY

The tests were run on the EPA versatile pilot-scale package boiler simulator (PBS) located at the Air and Energy Engineering Research Laboratory in Research Triangle Park, NC. The PBS configuration used for the refractory durability tests included the vertical down-fired precombustor section shown in Figure B-1. The facility was adapted to firing No. 6 residual oil, including oil preheater, filters, pumps, and transport lines. The facility was nominally fired on residual and distillate fuel oil during workdays and on gas during nights and weekends. The fuel changeovers at the start and the end of oil firing were done with a minimum of temperature excursions.

The test section with the light-weight Kaowool refractory was fabricated by the refractory manufacturer, Thermal Ceramics. The test section was positioned as the center spool in the down-fired precombustion section (refer to Figure B-1). This position provided the temperature window of interest of about 1540 °C (2800°F), and also was sufficiently downstream of the burner to allow oil volatilization.

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[1] The subscale refractory tests and the data analyses in this section were conducted by Ravi Srivastava of Acurex, Research Triangle Park, NC.

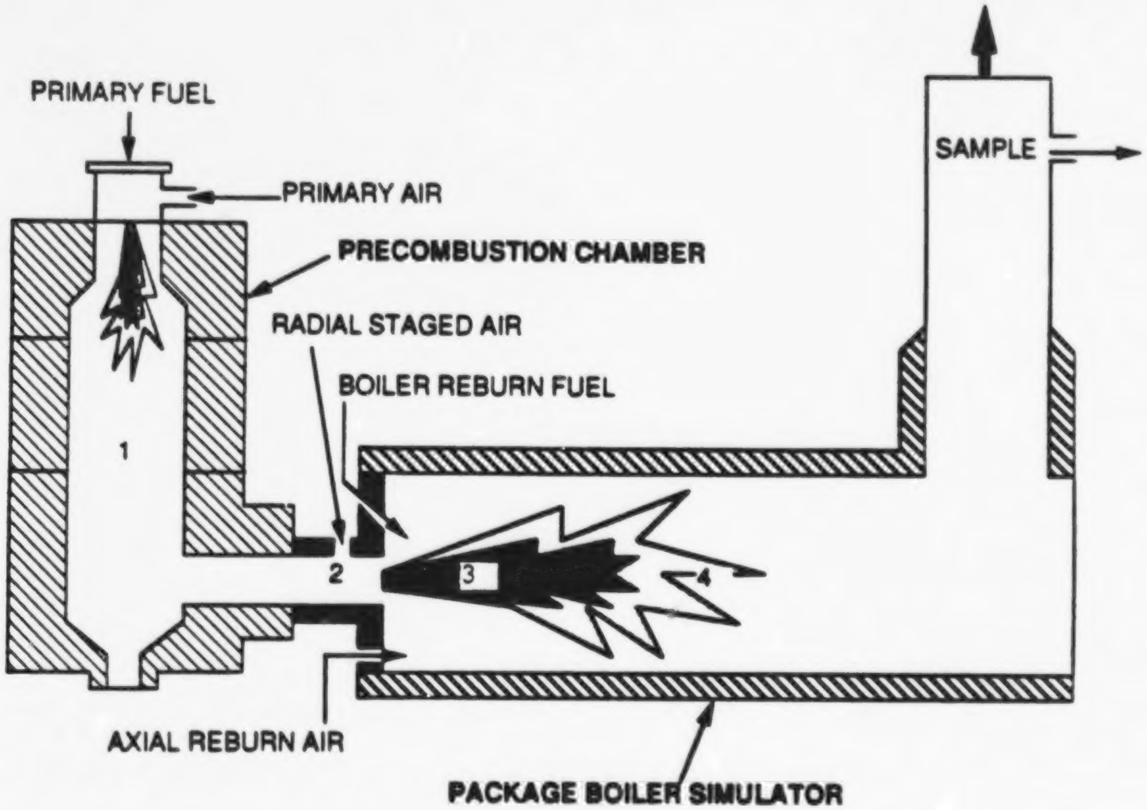

PRIMARY FUEL
PRIMARY AIR
PRECOMBUSTION CHAMBER
RADIAL STAGED AIR
BOILER REBURN FUEL
SAMPLE
1
2
3
4
AXIAL REBURN AIR
PACKAGE BOILER SIMULATOR

Figure B-1. EPA package boiler simulator.

Instrumentation was as is normally used with the PBS NO_x control testing. In addition, a thermocouple was positioned at the upstream plane of the refractory test section midway across the combustor flow. This was needed to monitor combustion gas temperatures to detect if the temperature limit of the material, 1566 °F (2850°F), was exceeded.

B.3 RESULTS

Table B-1 lists the operating log for the three test phases: quasi-steady, transient, and failure mode. The appearance of the refractory surface prior to the testing and during various stages of the tests is shown by the photos of the bore of the test spool on Figure B-2.

During the quasi-steady testing, various equipment malfunctions and scheduled maintenance necessitated several furnace shut-downs. The cold start-ups following a shut-down as well as other operational excursions resulted in more thermal transients than were specified in the test plan. Table B-2 lists the nominal steady-state test conditions during the first test phase. The transients which actually developed during the course of the quasi-steady testing are summarized on Table B-3. The NO_x levels indicated on the test summaries do not reflect the potential capabilities of this combustor. This is because in the subscale facility the heat losses are much higher than in the field, so the combustor temperatures were over 56°C (100°F) lower than the optimum in the fuel-rich precombustor for a given stoichiometric ratio. These lower temperatures slow the NO_x reduction reactions causing higher flue gas emissions than will be realized in a full scale combustor. The refractory after the 4-week quasi-steady test period showed no significant surface cracking or other signs of surface deterioration as shown on Figure B-2b. The rectangular chip missing from the surface coating at the top of the spool is thought to be mechanical damage during disassembly of the combustor for inspection.

During the transient testing phase, temperature cool-downs and ramp-ups were created in the combustor over a 5-day period. A cool-down episode was initiated by stopping the natural gas firing and purging the combustor with air. This would lower the temperature, T1, at the center of the combustor to below 815°C (1500°F). A ramp up condition was then created by firing at the maximum firing rate that the gas delivery system would allow at a slightly lean stoichiometry. After 15 minutes of this high fire, the fuel feedrate was reduced and the stoichiometric ratio was reduced to a fuel-rich condition. This would cause the centerline temperature, T1, to level off around 1540 °C (2800°F) within 15 minutes of the start of the ramp-up. After maintaining a temperature of 1540°C (2800°F) for over 15 minutes, the fuel was shut off and the air purge started to initiate another cool-down cycle.

Tables B-4 and B-5 show the operating conditions and temperature excursions throughout the 5 days of the transient testing. Figures B-3 through B-12 illustrate the temperature variations for the 5-test days. The temperature T2 at the edge of the refractory shows the same general trends of the gas temperature, T1, but exhibits lower temperature swings due to the wall conduction. The appearance of the refractory after transient testing as shown on Figure B-2c was very similar to the appearance after the quasi-steady tests.

Following the transient testing, a 32 cm^3 ($2\text{-in}^{3)}$ sample of each layer of the refractory was removed for inspection and analysis by the manufacturer. The final test phase to explore refractory failure limits was then started. The combustor temperatures were raised to levels beyond those recommended for continuous operation of the refractory. For this series, the furnace was fired with No. 2 oil since the hardware constraints allowed higher firing rates and temperatures with oil firing. The combustor was fired with No. 2 oil to maintain the center bore temperature near 150°C (300°F) for four periods of 8-hours each. The test spool was allowed to cool and inspected after the first 8-hour test period and then again after the final 8-hour

TABLE B-1. DURABILITY TESTING OPERATING LOG

DATE DATE FUEL START TIME (hrs) END TIME (hrs) TIME FIRED (hrs) FIRING RATE (MBtu/h) --------AVERAGE-------- O2 (%) CO (ppm) CO2 (%) NO (ppm) --START/FINISH-- T1 (F) T2 (F) REMARKS

DATE	DATE	FUEL	START	END	TIME	FIRING	--------AVERAGE--------				--START/FINISH--		
			TIME (hrs)	TIME (hrs)	FIRED (hrs)	RATE (MBtu/h)	O2 (%)	CO (ppm)	CO2 (%)	NO (ppm)	T1 (F)	T2 (F)	REMARKS
11/22/88	11/22/88	NG	9:00								70	70	INITIAL START UP.
11/23/88	11/23/88			8:30	23.5	9.98E+05	10.5	15	6.2		2700	2650	
11/23/88	11/23/88	#6	8:45								2750	2750	#6 RESERVOIR EMPTY,
11/23/88	11/23/88			11:15	2.5	2.02E+06	4.1	25	12.9		2700	2750	HOUSE #6 SYSTEM NOT FEEDING
11/23/88	11/23/88	NG	12:00								2000	2000	
11/23/88	11/23/88			14:30	2.5	9.98E+05	12.3	45	4.8		2650	2600	SHUT DOWN FOR THANKSGIVING.
11/28/88	11/28/88	NG	9:30								70	70	
11/29/88	11/29/88			7:00	21.5	9.98E+05	10.0	0	7.0		2800	2700	OVERTEMPERATURE SHUT OFF.
11/29/88	11/29/88	NG	8:00								2000	2000	FOUR 20 MIN. ATTEMPTS TO FIRE #6, COULD
11/30/88	11/30/88			8:00	24	9.98E+05	10.0	20	6.7		2400	2600	NOT ESTABLISH #6 FLOW: NOZZLE CLOGGED.
11/30/88	11/30/88	NG	8:00								2220	2500	SASS SAMPLING FOR EPA/CRB FOR 8 HRS.
12/01/88	12/01/88			8:30	24.5	9.98E+05	5.3	0	8.5		2220	2500	
12/01/88	12/01/88	NG	9:30								2300	2300	UNABLE TO FIRE #6 BECAUSE OF CLOGGED
12/01/88	12/01/88			13:00	3.5	9.98E+05	10.5	0	5.6		2660	2560	NOZZLE. RETURNED TO NG IDLE SETTINGS.
12/01/88	12/01/88	NG	13:30								2100	2100	UNABLE TO FIRE ON #6 BECAUSE OF CLOGGED
12/01/88	12/01/88			15:30	2	9.98E+05	10.5	0	5.6		2600	2420	NOZZLE. RETURNED TO NG IDLE SETTINGS.
12/01/88	12/01/88	#2	16:00								2500	2500	
12/01/88	12/01/88			16:15	0.25	2.07E+06					2700	2660	ESTABLISHED #2 FIRING.
12/01/88	12/01/88	NG	16:15								2350	2350	HOUSE FACILITIES SHUT FOR PREVENTIVE
12/01/88	12/01/88			16:30	0.25	9.98E+05	12.0	10	5.0		2760	2500	MAINTENANCE, FURNACE SHUT OFF.
12/05/88	12/05/88	NG	8:30								70	70	ON 12/06/88, UNABLE TO FIRE #6 AS DSU FEED
12/07/88	12/07/88			9:00	48.5	9.98E+05	10.3	40	6.0		2600	2360	RESERVOIR WAS COLD. ESTABLISHED #2 FIRING.
													SET UP RECIRCULATION OF #6 THRU HEATER.
													INSTALLED A HEATER BYPASS FOR #2 FIRING.
12/07/88	12/07/88	#6	9:00								2600	2600	OVERTEMPERATURE SHUT OFF CAUSED BY
12/07/88	12/07/88			13:30	4.5	2.02E+06	3.0	15	15.0		2800	T/C BURNT	LOW #6 FLOW DUE TO NOZZLE CLOG.
													DSU SHUT DOWN FOR BURNER REPAIRS.
12/08/88	12/08/88	NG	10:00								CHART	EXHAUSTED	START UP AFTER REPAIRS.
12/09/88	12/09/88			9:30	23.5	9.98E+05	10.0	5	6.0		2500	T/C BURNT	
12/09/88	12/09/88	#6	9:30										
				12:30	3	2.02E+06	4.0	10	13.0		2600	T/C BURNT	#6 RESERVOIR EMPTY, ATTEMPTS TO FIRE
											2700	T/C BURNT	FROM HOUSE SUPPLY FAILED. STARTED FILLING
													RESERVOIR FROM HOUSE SUPPLY.

TABLE B-1. (continued)

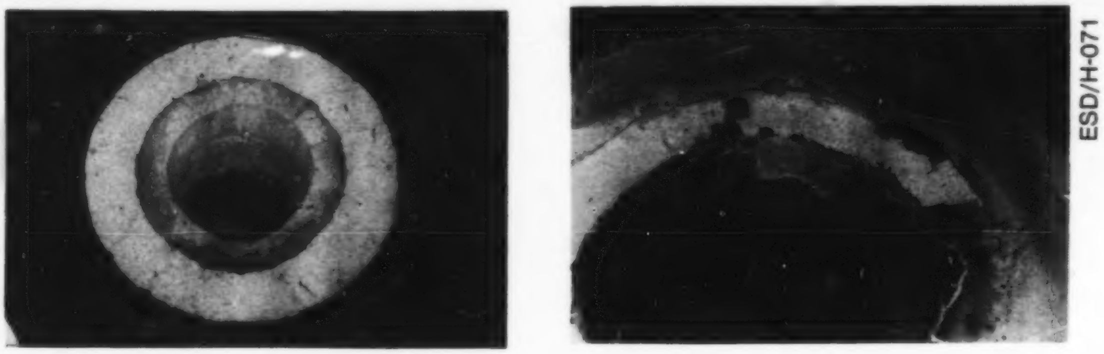
DATE	DATE	FUEL	START TIME (hrs)	END TIME (hrs)	TIME FIRED (hrs)	FIRING RATE (MBtu/h)	--------AVERAGE--------				--START/FINISH--		REMARKS
							O2 (%)	CO (ppm)	CO2 (%)	NO (ppm)	T1 (F)	T2 (F)	
12/09/88	12/09/88	NG	13:00								2300	T/C BURNT	#6 LINES COLD MONDAY MORNING; BACK
12/12/88	12/12/88			13:00	72	9.98E+05	10.7	0	5.3		2620	T/C BURNT	PRESSURE REGULATOR NOT RELIEVING. CLEANED THE REGULATOR.
12/12/88	12/12/88	#6	13:00								2600	T/C BURNT	OVERTEMPERATURE SHUT OFF.
12/12/88	12/12/88			15:30	2.5	2.02E+06	4.5	20	10.4		2800	T/C BURNT	
12/12/88	12/12/88	#2	16:00								2660	T/C BURNT	
12/12/88	12/12/88			16:15	0.25	2.07E+06	5.3	20	8.4		2660	T/C BURNT	FIRED ON #2 FUEL OIL.
12/12/88	12/12/88	NG	16:15								2200	T/C BURNT	
12/13/88	12/13/88			8:30	16.25	9.98E+05	8.8	25	5.2		2400	T/C BURNT	
12/13/88	12/13/88	#6	8:30								2370	T/C BURNT	OVERTEMPERATURE SHUT OFF DUE TO #6
				11:30	3	2.02E+06	3.5	15	12.6		2800	T/C BURNT	FLOW DECREASE. ATTEMPTS TO FILL #6 RESERVOIR FROM HOUSE SUPPLY UNSUCCESSFUL DUE TO HEATERS ON HOUSE SYSTEM INOPERATIVE
12/13/88	12/13/88	NG	13:00								1800	T/C BURNT	UNABLE TO GET ANY #6 FROM HOUSE SUPPLY
12/15/88	12/15/88			12:30	47.5	9.98E+05	10.0	20	6.0		2460	T/C BURNT	UNTIL NOON OF 12/15/88.
12/15/88	12/15/88	#6	12:45								2480	T/C BURNT	
12/15/88	12/15/88			15:15	2.5	2.02E+06	2.5	50	18.0	120	2620	T/C BURNT	VERY ERRATIC #6 FLOW.
12/15/88	12/15/88	#2	15:15								2660	T/C BURNT	
12/15/88	12/15/88			15:30	0.25	2.07E+06					2660	T/C BURNT	BRIEF FIRING OF #2.
12/15/88	12/15/88	NG	15:30								2240	T/C BURNT	
12/16/88	12/16/88			9:00	17.5	9.98E+05	12.1	20	4.7	60	2600	T/C BURNT	IDLING.
12/16/88	12/16/88	#6	9:15								2600	T/C BURNT	OVERTEMPERATURE SHUT OFF PROBABLY DUE
12/16/88	12/16/88			12:45	3.5	2.02E+06	2.5	28	13.2	140	2800	T/C BURNT	TO FAILING T/C. SHUT DOWN FOR THE WEEKEND IN THE ABSENCE OF OVERTEMP PROTECTION.
12/19/88	12/19/88	NG	12:45								70	T/C BURNT	T/C REPAIRED AND FURNACE BROUGHT UP.
12/20/88	12/20/88			10:00	21.25	9.98E+05	10.0	16	6.5	20	2260	T/C BURNT	
12/20/88	12/20/88	NG	10:00								2260	T/C BURNT	NATURAL GAS DATA AQUISITION.
				13:00	3	1.87E+06					2480	T/C BURNT	
12/20/88	12/20/88	#6	13:15								2400	T/C BURNT	T/C FAILED. T/C WIRE ORDERED.
				15:15	2	2.02E+06	3.0	28	12.0	160	2700	T/C BURNT	
01/03/89	01/03/89	NG	9:45								70	70	COOLANT OVERHEAT. COOLANT PUMP STARTED.
01/03/89	01/03/89			11:00	1.25	9.98E+05	10.1	30	9.2	75	1960	1750	
01/03/89	01/03/89	NG	11:15								1700	1300	T/C PROVIDED BY MVD FAILED.
01/03/89	01/03/89			14:00	2.75	9.98E+05	9.8	35	9.2	60	2560	2300	
01/16/89	01/16/89	NG	10:00								70	T/C BURNT	LOOSE T/C WIRE CAUSED OVERTEMP SHUTDOWN.
01/17/89	01/17/89			2:00	16	9.98E+05		0	9.4	0	2800	T/C BURNT	

TABLE B-1. (continued)

DATE	DATE	FUEL	START TIME (hrs)	END TIME (hrs)	TIME FIRED (hrs)	FIRING RATE (MBtu/h)	AVERAGE O2 (%)	AVERAGE CO (ppm)	AVERAGE CO2 (%)	AVERAGE NO (ppm)	START/FINISH T1 (F)	START/FINISH T2 (F)	REMARKS
01/17/89	01/17/89	NG	10:15								1850	T/C BURNT	FURNACE RE-HEATED AFTER SHUTDOWN.
01/17/89	01/17/89			15:00	4.75	9.90E+05	10.9	0	10.0	35	2400	T/C BURNT	
01/17/89	01/17/89	NG	15:00								2400	T/C BURNT	SET UP NEW LOW IDLE SETTINGS.
01/17/89	01/17/89			17:00	2	8.15E+05	10.2	0	10.6	35	2300	T/C BURNT	
01/17/89	01/17/89	NG	17:00								2240	T/C BURNT	TRIAL HIGH FIRE SETTINGS.
01/17/89	01/17/89			17:30	0.5	1.60E+06	8.0	0	11.8	300	2400	T/C BURNT	
01/17/89	01/17/89	NG	17:30								2600	T/C BURNT	OVERNIGHT IDLING.
01/18/89	01/18/89			8:30	15	8.15E+05	7.1	0	12.4	50	2400	T/C BURNT	
01/18/89	01/18/89	NG	8:30								-	T/C BURNT	TRANSIENT SETTING DETERMINATION.
01/18/89	01/18/89			18:00	9.5	VARIOUS	-	-	-	-	-	T/C BURNT	
01/18/89	01/18/89	NG	18:00								2800	T/C BURNT	OVERNIGHT IDLING.
01/19/89	01/19/89			10:00	16	7.10E+05	12.3	35	9.0	30	2400	T/C BURNT	
01/19/89	01/19/89	NG	10:00								-	T/C BURNT	TRANSIENT TESTING: DAY 1.
01/19/89	01/19/89			17:15	6.25	VARIOUS	-	-	-	-	-	-	
01/19/89	01/19/89	NG	17:15								1400	2000	OVERNIGHT IDLING.
01/20/89	01/20/89			8:30	15.25	7.10E+05	11.7	45	8.8	20	2560	2380	
01/20/89	01/20/89	NG	8:30								-	-	TRANSIENT TESTING: DAY 2.
01/20/89	01/20/89			15:00	6.5	VARIOUS	-	-	-	-	-	-	
01/20/89	01/20/89	NG	15:00								1700	2100	WEEKEND IDLING.
01/23/89	01/23/89			9:00	66	7.10E+05	5.7	45	12.0	30	2750	2600	
01/23/89	01/23/89	NG	9:00								-	-	TRANSIENT TESTING: DAY 3.
01/23/89	01/23/89			15:30	6.5	VARIOUS	-	-		-	-	-	
01/23/89	01/23/89	NG	15:30								1200	1800	OVERNIGHT IDLING.
01/24/89	01/24/89			9:00	17.5	7.10E+05	10.6	80		75	2640	2480	
01/24/89	01/24/89	NG	9:00								-	-	TRANSIENT TESTING: DAY 4.
01/24/89	01/24/89			15:30	6.5	VARIOUS	-	-		-	-	-	
01/24/89	01/24/89	NG	15:30								1400	2000	OVERNIGHT IDLING.
01/25/89	01/25/89			7:45	16.25	7.10E+05	4.5	0		50	2500	2320	
01/25/89	01/25/89	NG	7:45								-	-	TRANSIENT TESTING: DAY 5.
01/25/89	01/25/89			15:15	7.5	VARIOUS	-	-		-	-	-	
01/25/89	01/25/89	NG	15:15								2400	2500	HIGH FIRNG
01/25/89	01/25/89			17:30	2.25	1.50E+06	4.5	50		100	2800	2450	
01/25/89	01/25/89	NG	17:30								2800	2450	LONG TERM IDLING. CEMS SWITCHED OFF.
02/02/89	02/02/89			14:00	188.5	7.10E+05					2400	2300	SHUT OFF FOR PHOTOGRAPHING OF TEST SPOOL.

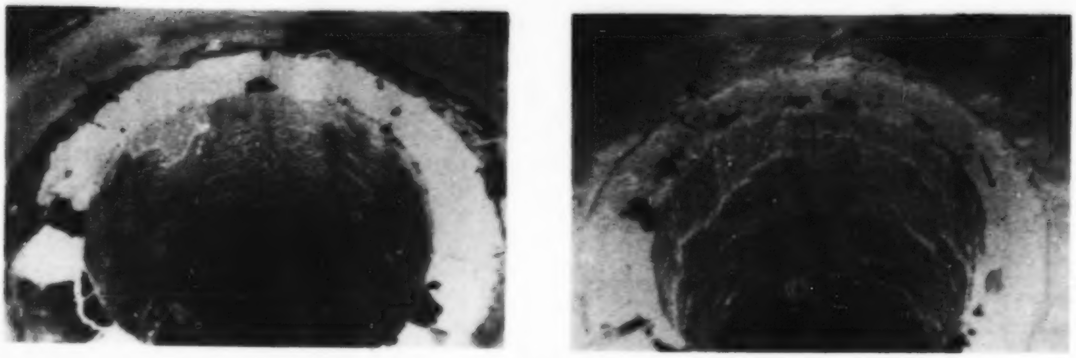
TABLE B-1. (continued)

DATE	DATE	FUEL	START TIME (hrs)	END TIME (hrs)	TIME FIRED (hrs)	FIRING RATE (MBtu/h)	AVERAGE O2 (%)	CO (ppm)	CO2 (%)	NO (ppm)	START/FINISH T1 (F)	T2 (F)	REMARKS
02/14/89	02/14/89	NG	17:15								70	70	START UP FOR FAILURE TESTING.
02/15/89	02/15/89			8:30	15.25	9.90E+05	10.6	10	9.4	300	2560	2640	
02/15/89	02/15/89	NG	8:30								2560	2640	SWITCHED TO IDLE SETTINGS.
02/15/89	02/15/89			9:30	1	9.90E+05	8.4	10	10.7	75	2500	2380	
02/15/89	02/15/89	NG	9:30								2500	2380	HIGH FIRE SETTING DETERMINATION.
02/15/89	02/15/89			12:00	2.5	1.72E+06	-	-	-	-	2510	2670	
02/15/89	02/15/89	NG	12:00								2510	2670	ATTEMPT TO ATTAIN 3000 DEGREES WHILE
02/15/89	02/15/89			15:00	3	1.00E+06	7.0	15	11.6	230	2600	2650	FIRING ON NATURAL GAS
02/15/89	02/15/89	#2	15:15								2240	2360	#2 FUEL OIL SETTING VERIFICATION
02/15/89	02/15/89			17:30	2.25	1.96E+06	6.2	27	14.2	890	2980	2700	
02/15/89	02/15/89	NG	17:30								2980	2700	OVERNIGHT IDLING.
02/16/89	02/16/89			9:30	16	9.90E+05	7.4	30	11.5	40	2340	2480	
02/16/89	02/16/89	#2	9:45								2340	2480	BORE TEMPERATURES MAINTAINED NEAR 3000.
02/16/89	02/16/89			10:00	0.25	VARIOUS	-	-		-	2980	2580	SHUT OFF FOR PHOTOGRAPHING OF TEST SPOOL.
02/20/89	02/20/89	NG	11:00								70	70	START UP FOR CONTINUED FAILURE TESTING.
02/21/89	02/21/89			10:30	23.5	9.90E+05	8.9	40	10.0	240	2550	2680	
02/21/89	02/21/89	#2	10:30								2550	2680	FAILURE TESTING. DAY 2.
02/21/89	02/21/89			18:30	8	1.70E+06	7.5	50	13.0	700	2996	2800	
02/21/89	02/21/89	NG	18:45								2996	2800	OVERNIGHT IDLING.
02/22/89	02/22/89			8:45	14	9.90E+05	6.9	38	11.4	35	2470	2540	
02/22/89	02/22/89	#2	9:00								2470	2540	FAILURE TESTING. DAY 3.
02/22/89	02/22/89			17:00	8	1.80E+06	7.2	40	13.2	700	2987	2800	
02/22/89	02/22/89	NG	17:00								2987	2800	OVERNIGHT IDLING.
02/23/89	02/23/89			10:00	17	9.90E+05	7.5	40	11.3	50	2430	2220	
02/23/89	02/23/89	#2	10:00								2430	2220	FAILURE TESTING. DAY 4
02/23/89	02/23/89			18:00	8	1.80E+06	7.2	10	13.1	800	2996	2030	SHUT OFF FOR PHOTOGRAPHING OF TEST SPOOL.



a. Before testing

b. After Quasi-steady tests



c. After Transient tests

d. After Overtemperature tests

Figure B-2. Refractory response to durability testing.

TABLE B-2. STEADY STATE ENDURANCE TESTING (PHASE I)

FUEL	TEMPERATURE RANGE, T1 (F)	TOTAL HOURS	O2 (%)	EMISSIONS NO (ppm)	CO (ppm)	CO2 (%)	Trace Reference
NG	2200-2800	330	5.3-10.7	5-100	0-50	7-8.5	(11-22,23-88) (11-28,29,30-88) (12-1,5,9-88) (12-13,14,15-88) (12-19,20-88) (1-16,17,18-89) (1-19,20-89) (1-23,24,25-89)
#2	2660	0.5	10.3-10.7	30-50	0-20	4.2-4.8	none
#6	2600-2800	19.5	2.6-4.4	120-160	10-30	12.2-18	(11-23-88) (12-7,9,12-88) (12-13,16,20-88)

FUEL	TEMPERATURE RANGE, T1 (F)	HOURS	O2 (%)	EMISSIONS NO (ppm)	CO (ppm)	CO2 (%)	Trace Reference

TABLE B-3. TRANSIENT OPERATION OCCURRING DURING PHASE I

FUEL	TEMPERATURE RANGE, T1 (F)	HOURS	O2 (%)	EMISSIONS NO (ppm)	CO (ppm)	CO2 (%)	Trace Reference
NG	70-2700	13.50	10.4		15-25	6.2	(11-22-88)
	1600-2700	1.00	12.2		45-50	4.8-5	(11-23-88)
	70-2600	14.00	10.4		10-40	6.6-7	(11-28-88)
	2000-2600	0.50	10.0		0	7.4	(11-29-88)
	1600-2550	0.67	10.2		20	7.0	(11-29-88)
	2000-2600	0.33	10.2		20	7.0	(11-29-88)
	1500-2300	0.50	10.1		20	7.0	(11-29-88)
	1500-2400	0.75	10.1		20	7.0	(11-29-88)
	1500-2660	1.00	10.3		0	5.6	(12-1-88)
	1600-2640	0.75	10.4		0	5.9	(12-1-88)
	2400-2700	0.25	12.1		0-40	5.0	(12-1-88)
	70-2750	4.50	10.2		30-250	5.6-6	(12-5-88)
	<1000-2600	4.00					none
	1500-2640	0.50	10.7		10	5.3	(12-9-88)
	2000-2600	0.25	10.6		10	5.2	(12-9-88)
	1950-2400	0.25	8.8		15-20	5.4	(12-12-88)
	1000-2300	1.50	9.4		0	6-6.5	(12-13-88)
	1600-2400	1.00	8.8		0	5.6-6.2	(12-13-88)
	70-2200	3.00	10.2	20-80	0-130	4.8-5.6	(12-19-88)
	2200-2550	0.75	5-7	70-90	10-20	7-8.5	(12-20-88)
	70-1950	1.00	10.1	40-80	40-50	9-9.2	(1-3-89)
	700-2600	3.00	10.1	70-150	40-50	9-9.2	(1-3-89)
	70-2400	4.00		0	0	9.4	(1-16-89)
	1400-2400	1.00	10.9	25	0	10.0	(1-17-89)
	2460-2380	0.50	11.5	30	0	9.6	(1-17-89)
	2260-2400	0.50	8.0	35-300	0	12.0	(1-17-89)
	2540-2400	0.50	7.1	45	0	12.4	(1-17-89)
	2200-2620	8.00					(1-18-89)
	2800-2400	2.00	12.3-12.5	30-50	0-40	8.8-9.0	(1-18-89)
Total hours NG		53					
#2	2500-2700	.25	4.5-6		0	11-12	(12-1-88)
	2500-2700	.25	4.5-6		20	11-12	none
Total hours #2		0.5					
#6	2200-2700	0.5	4-4.5		25	12.7-13.6	(11-23-88)
	2000-2700	.25	3-3.6		10-15	12-12.5	(12-13-88)
	2400-2750	2.5	1.5-4	80-140	45-55	15.6-18.4	(12-15-88)
	2450-2700	1	4-6.7	140-200	20-30	11.6-12.7	(12-20-88)
Total hours #6		4.25					

TABLE B-4. TRANSIENT TESTING OF LIGHTWEIGHT REFRACTORY SPOOL—EMISSIONS

1-19-89

			Emissions (at 0% O2)			
FR (Btu/h)	SR1	SR2	CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
1.08E+06	0.98	1.23	22.61	110	192	2,3
1.63E+06	1.04	1.44	23.64	535	591	3,4,5
1.08E+06	0.99	1.59	24.61	175	278	5,6,7
1.63E+06	1.04	1.20	22.06	256	549	8,9,10,11
1.08E+06	0.98	1.23	22.04	133	275	11,12,13
1.63E+06	1.04	1.20	21.82	193	661	14,15,16,17
1.08E+06	0.92	1.17	21.37	114	151	17,18,19,20,21
1.63E+06	1.04	1.20	21.97	214	591	22,23,24,25
1.08E+06	0.92	1.17	22.57	131	256	25,26,27
1.63E+06	1.03	1.20	21.83	185	684	28,29.30,31
1.08E+06	0.92	1.17	21.66	131	148	31,32,33,34,35
1.58E+06	1.07	1.23	22.19	151	605	36,37,38,39
1.08E+06	0.85	1.10	21.31	116	69	39,40,41

TABLE B-4. (continued)

1-20-89

FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
1.61E+06	1.05	1.21	16.39	73	657	3,4,5,6
1.08E+06	0.85	1.10	15.54	52	63	6,7,8
1.61E+06	1.05	1.21	16.40	78	620	9,10,11,12
1.08E+06	0.85	1.10	15.61	58	70	12,13,14
1.61E+06	1.04	1.21	16.36	67	465	15,16,17,18
1.08E+06	0.85	1.10	15.57	58	62	18,19,20
1.61E+06	1.05	1.21	16.34	71	549	21,22,23,24
1.08E+06	0.85	1.10	15.59	54	66	24,25,26
1.61E+06	1.04	1.21	16.33	64	389	27,28,29,30
1.08E+06	0.85	1.10	15.62	56	64	30,31,32
1.61E+06	1.05	1.21	16.34	67	470	33,34,35,36
1.08E+06	0.85	1.10	15.63	54	70	36,37,38

1-23-89

TABLE B-4. (continued)

FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
1.08E+06	0.88	1.13	NA	36	91	6,7,8
1.54E+06	1.11	1.28	NA	37	401	9,10,11,12
1.08E+06	0.93	1.18	NA	36	138	12,13,14
1.54E+06	1.11	1.28	NA	49	547	15,16,17,18
1.08E+06	0.95	1.19	NA	45	138	18,19,20,21
1.54E+06	1.10	1.28	NA	54	592	22,23,24,25
1.08E+06	0.96	1.20	NA	52	173	25,26,27,28
1.54E+06	1.11	1.28	NA	60	536	29,30,31,32
1.08E+06	0.92	1.17	NA	57	130	32,33,34
1.54E+06	1.10	1.28	NA	89	517	35,36,37,38
1.08E+06	0.95	1.19	NA	111	149	38,39,40

1-24-89

TABLE B-4. (continued)

FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
1.56E+06	1.09	1.26	NA	103	583	3,4,5,6
1.08E+06	0.98	1.23	NA	94	214	6,7,8,9
1.56E+06	1.09	1.26	NA	105	623	10,11,12,13
1.08E+06	0.98	1.22	NA	104	273	13,14,15
1.56E+06	1.09	1.26	NA	110	687	16,17,18,19
1.08E+06	0.87	1.11	NA	98	96	19,20,21,22
1.56E+06	1.09	1.26	NA	118	615	23,24,25,26
1.08E+06	0.91	1.16	NA	101	138	26,27,28,29
1.56E+06	1.09	1.26	NA	115	580	30,31,32,33
1.08E+06	0.91	1.16	NA	101	137	33,34,35
1.56E+06	1.09	1.26	NA	118	636	36,37,38,39
1.08E+06	0.90	1.15	NA	100	126	39,40,41

1-25-89

TABLE B-4. (continued)

FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
1.58E+06	1.08	1.25	NA	111	554	3,4,5,6
1.08E+06	0.87	1.12	NA	72	96	11,12,13
1.58E+06	1.08	1.25	NA	82	545	14,15,16,17
1.08E+06	0.90	1.14	NA	75	118	17,18,19
1.58E+06	1.07	1.24	NA	90	554	20,21,22,23
1.08E+06	0.89	1.14	NA	73	119	31,32,33
1.58E+06	1.07	1.24	NA	88	543	34,35,36,37
1.08E+06	0.89	1.14	NA	83	119	37,38,39
1.58E+06	1.06	1.23	NA	72	286	40,41,42,43,44,45
1.08E+06	0.89	1.14	NA	76	113	45,46,47
1.58E+06	1.06	1.23	NA	68	291	48,49,50,51
1.08E+06	0.88	1.13	NA	83	115	51,52,53

TABLE B-5. TRANSIENT TESTING OF LIGHTWEIGHT REFRACTORY SPOOL—TEMPERATURES

Temperatures

Pt. #	1-19-89			1-20-89			1-23-89			1-24-89			1-25-89		
	Time (min)	T1 (F)	T2 (F)	Time (min)	T1 (F)	T2 (F)	Time (min)	T1 (F)	T2 (F)	Time (min)	T1 (F)	T2 (F)	Time (min)	T1 (F)	T2 (F)
1	0	2340		0	2560	2380	0	2740	2580	0	2680	2520	0	2540	2370
2	5	2340		35	2560	2380	35	2740	2580	35	2680	2520	25	2540	2370
3	77	2480		48	1320	1970	48	1680	2180	48	1560	2040	38	1600	1940
4	78	2410		49	2300	2140	49	2300	2400	49	2240	2410	39	2140	2240
5	95	2515		55	2440	2360	55	2400	2460	55	2320	2460	45	2260	2400
6	97	2760		65	2520	2500	65	2440	2490	65	2380	2540	55	2320	2480
7	135	2800		66	2810	2510	66	2790	2570	66	2760	2440	56	2680	2400
8	148	1290		95	2810	2520	95	2810	2610	75	2800	2490	65	2760	2440
9	150	2220		108	1360	1980	108	1440	2040	95	2820	2520	100	2780	2480
10	155	2340	2320	110	2340	2330	110	2240	2320	108	1340	1940	101	2410	2560
11	165	2440	2420	115	2440	2420	115	2370	2500	110	2220	2340	115	2420	2610
12	170	2780	2460	125	2500	2470	125	2430	2540	115	2340	2460	116	2800	2520
13	205	2820	2510	126	2820	2500	126	2800	2540	125	2420	2560	145	2800	2520
14	218	1370	2010	155	2820	2520	155	2820	2590	126	2780	2500	158	1440	1990
15	220	2360	2350	168	1270	1940	168	1380	2000	155	2820	2530	160	2200	2320
16	225	2380	2370	170	2240	2180	170	2080	2280	168	1440	2000	165	2320	2460
17	235	2480	2450	175	2440	2430	175	2350	2440	170	2280	2380	175	2380	2540
18	237	2590	2460	185	2490	2460	185	2430	2540	175	2390	2510	177	2800	2480
19	245	2610	2490	187	2810	2480	187	2740	2540	185	2430	2560	205	2800	2520
20	246	2810	2510	215	2810	2510	195	2800	2580	187	2780	2490	218	1470	2000
21	265	2810	2540	228	1340	1960	215	2810	2630	195	2820	2530	220	2220	2360
22	278	1380	2020	230	2240	2220	228	1400	2060	215	2820	2530	225	2320	2460
23	280	2300	2280	235	2400	2390	230	2240	2345	228	1440	1980	235	2380	2560
24	285	2400	2390	245	2500	2480	235	2380	2470	230	2280	2370	236	2680	2470
25	295	2490	2470	246	2820	2490	245	2440	2540	235	2380	2520	250	2730	2480
26	298	2800	2500	275	2820	2510	246	2740	2540	245	2440	2560	251	2390	2580
27	325	2820	2540	288	1380	1980	255	2800	2580	246	2780	2520	265	2410	2600
28	338	1360	2000	290	2340	2240	275	2810	2620	255	2820	2540	266	2740	2530
29	340	2380	2360	295	2420	2420	288	1360	2020	275	2820	2540	280	2740	2520
30	345	2440	2430	305	2500	2500	290	2220	2340	288	1420	1980	281	2420	2600
31	355	2520	2500	307	2820	2480	295	2360	2460	290	2260	2360	300	2450	2650
32	357	2650	2510	335	2820	2490	305	2460	2520	295	2400	2500	301	2800	2570
33	363	2680	2530	348	1360	1980	307	2800	2520	305	2440	2570	325	2800	2570
34	364	2820	2540	350	2240	2260	335	2820	2630	307	2800	2500	338	1640	2080
35	385	2820	2550	355	2440	2440	348	1380	2020	335	2810	2540	340	2240	2380
36	398	1380	2000	365	2520	2520	350	2260	2340	348	1440	2000	345	2400	2540
37	400	2420	2260	366	2820	2480	355	2400	2500	350	2240	2380	355	2450	2620
38	405	2560	2410	395	2820	2520	365	2460	2540	355	2360	2500	356	2800	2540
39	415	2660	2500	408	1740	2160	366	2800	2540	365	2400	2560	385	2800	2540
40	416	2820	2560	410	2500	2330	395	2820	2640	366	2790	2490	398	1590	2060
41	445	2820	2580	415	2580	2400	408	1220	1860	395	2820	2540	400	2160	2300
42	458	1440	2080	420	2590	2420	410	2440	2180	408	1480	2040	405	2240	2400
43	460	2430	2260	460	2550	2420	415	2580	2340	410	2300	2440	410	2250	2410
44	465	2540	2330	500	2550	2420	440	2660	2470	415	2400	2540	411	2340	2500
45	475	2620	2400				470	2680	2510	430	2440	2560	425	2460	2610
46	485	2640	2440				500	2680	2510	500	2440	2560	426	2800	2520
47	500	2640	2440										445	2800	2530
48													458	1620	2060
49													460	2300	2400
50													465	2420	2540
51													475	2500	2620
52													476	2810	2540
53													500	2810	2540

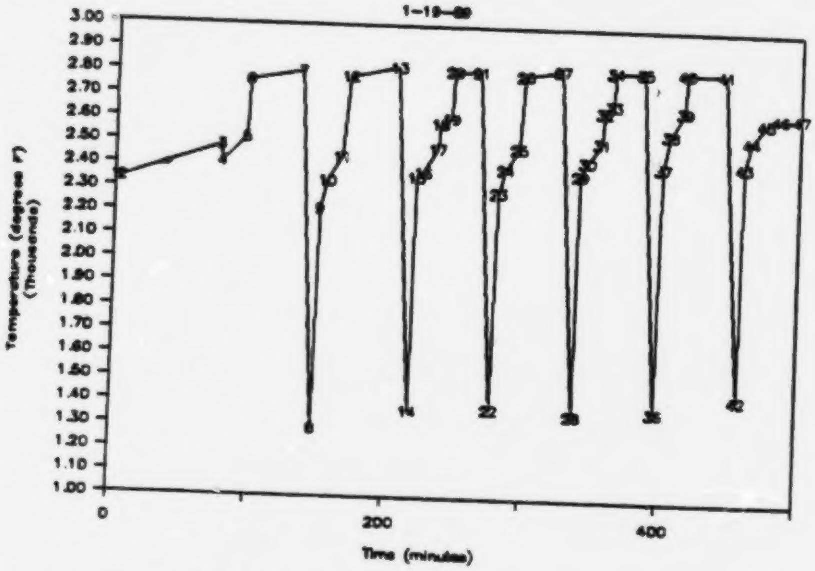


Figure B-3. Transient bore temperatures (T1)—1-19-89.

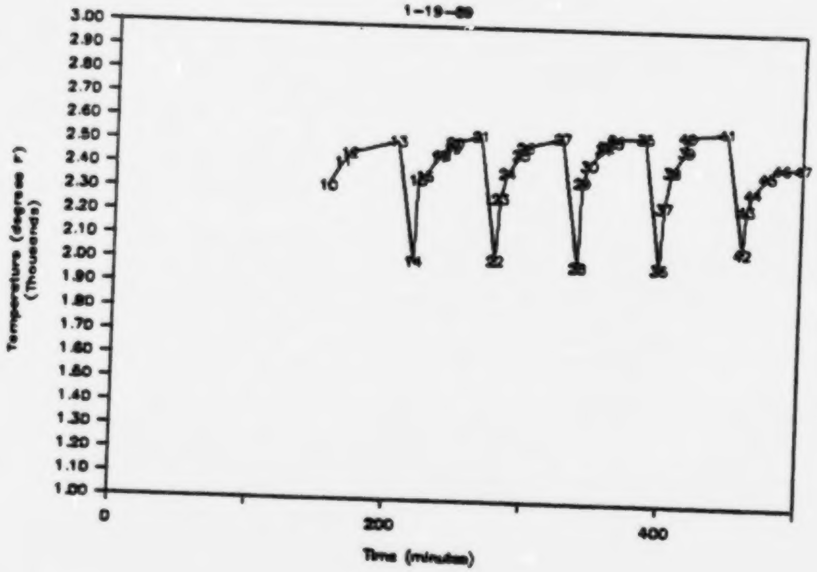


Figure B-4. Transient inner spool temperatures (T2)—1-19-89.

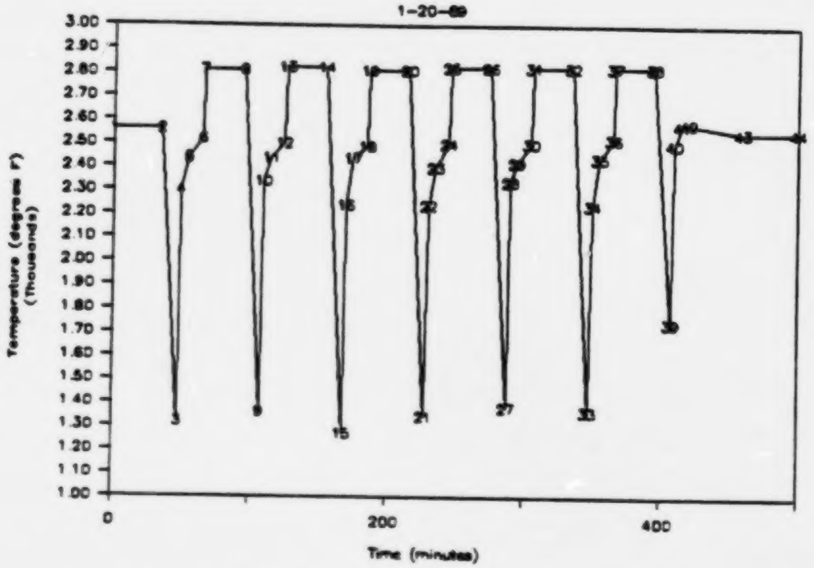


Figure B-5. Transient bore temperatures (T1)—1-20-89.

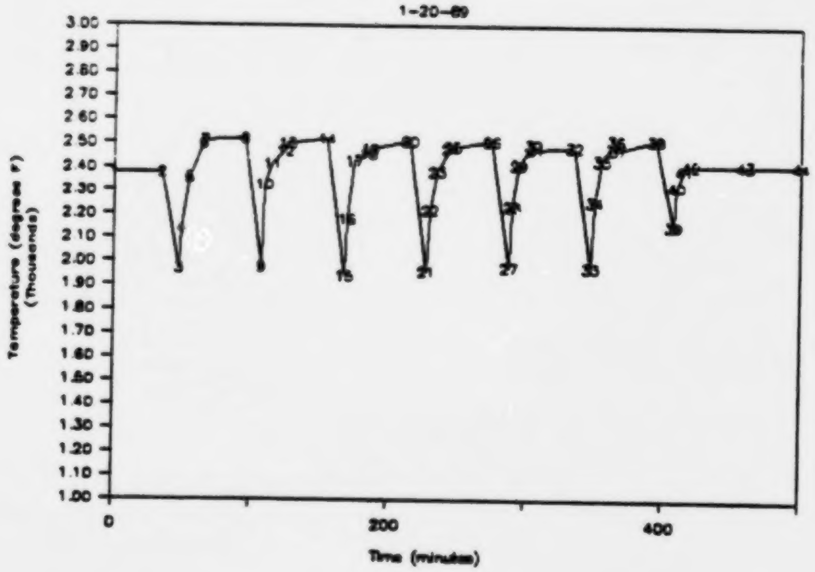


Figure B-6. Transient inner spool temperatures (T2)—1-20-89.

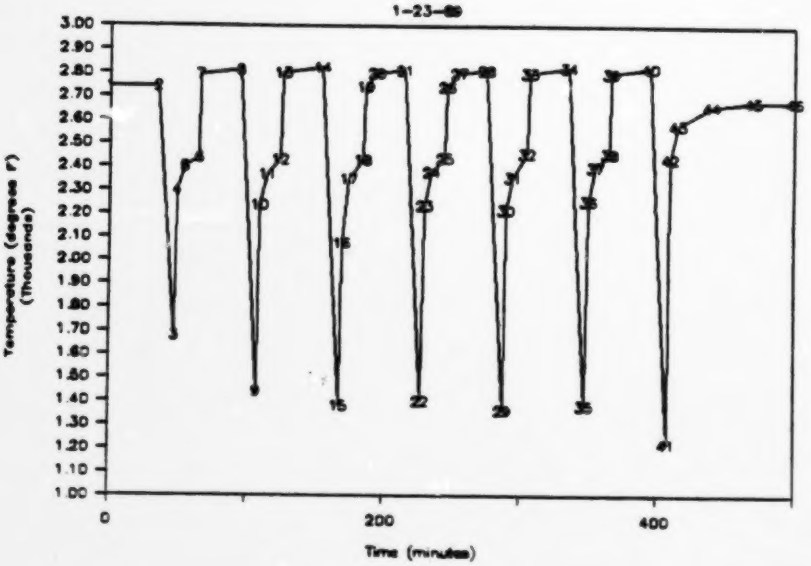


Figure B-7. Transient bore temperatures (T1)—1-23-89.

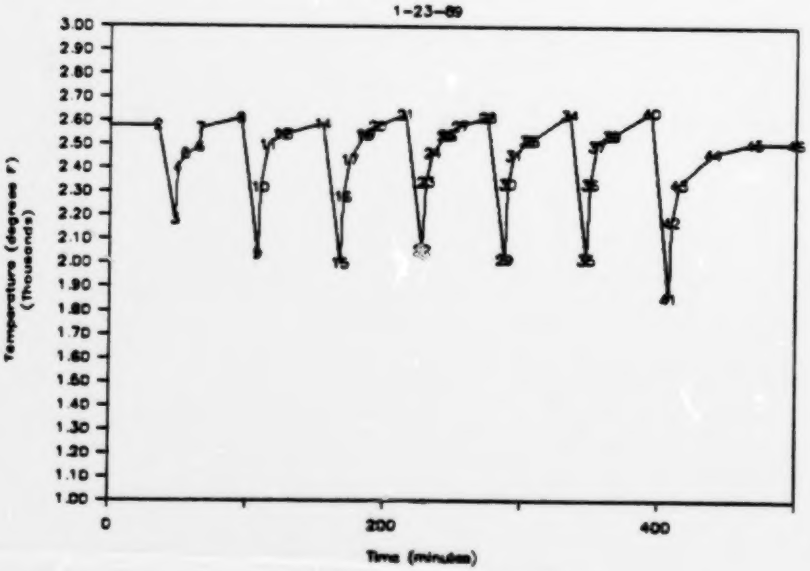


Figure B-8. Transient inner spool temperatures (T2)—1-23-89.

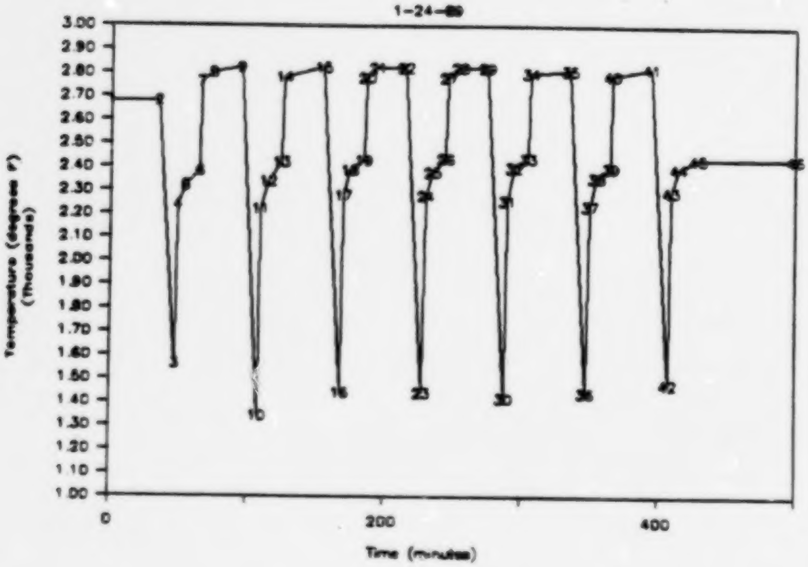


Figure B-9. Transient bore temperatures (T1)—1-24-89.

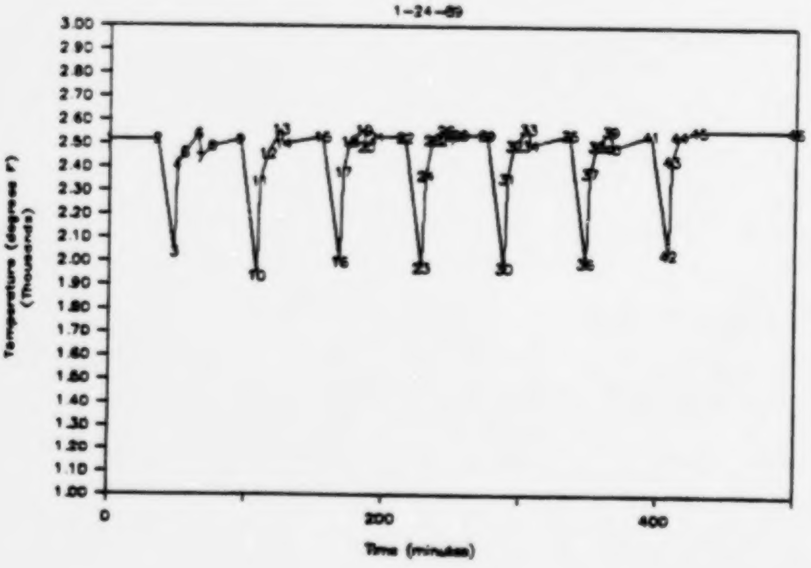


Figure B-10. Transient inner spool temperatures (T2)—1-24-89.

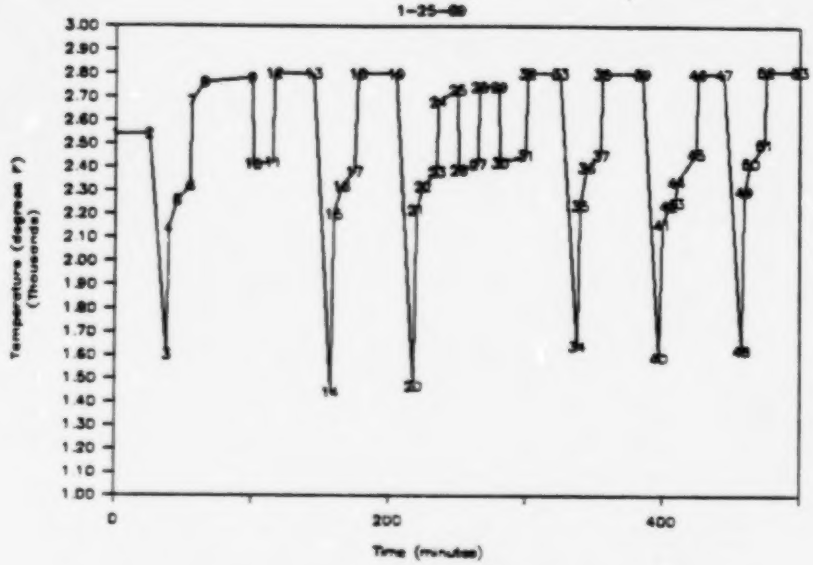


Figure B-11. Transient bore temperatures (T1)—1-25-89.

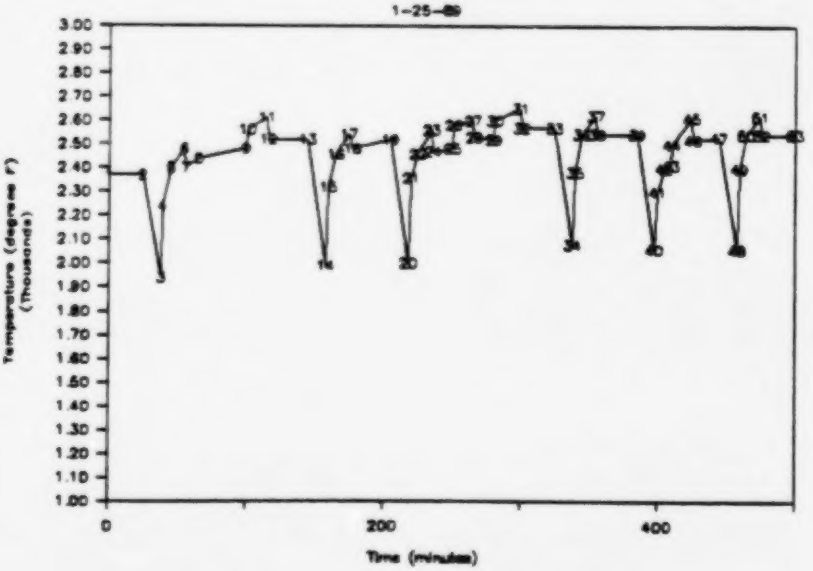


Figure B-12. Transient inner spool temperatures (T2)—1-25-89.

test. Tables B-6 and B-7 summarize the temperature and emissions data during the failure mode overtemperature testing. The plots of temperatures are shown on Figures B-13 through B-22. The refractory condition at the conclusion of the overtemperature testing is shown on photo B-2d. The primary effects of excursions above 1566°C (2850°F) appeared to be deterioration of the Unikote surface coating. This coating was largely intact at the start of the failure tests,but was approximately 25 percent gone after the four 8-hour tests. The manufacturer indicated the primary function of the coating is for added structural integrity during installation. At this stage, the uncured refractory is soft and pliable. After the initial firing and curing, the pyroblock becomes hard and the coating has little additional value. Apart from the loss of the Unikote, the surface showed no other significant cracking or other signs of deterioration.

TABLE B-6. FAILURE TESTING OF LIGHTWEIGHT REFRACTORY SPOOL—EMISSIONS

Date: 2-15-89

Fuel	FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
NG	9.98E+05	1.06	1.71	18.98	20	606	0,1
NG	9.98E+05	0.81	1.72	17.83	17	117	2,3
NG	9.98E+05	1.06	1.71	18.98	30	121	4,5
NG	1.72E+06	0.79	1.23	16.61	21	618	6,7
NG	1.72E+06	0.99	1.23	17.05	20	641	6,7
NG	1.72E+06	0.93	1.17	16.43	20	457	6.7
NG	1.72E+06	0.91	1.15	16.26	19	397	6,7
NG	1.03E+06	1.11	1.50	17.40	23	345	8,9
#2	1.96E+06	1.07	1.34	20.15	38	1277	10,11,12

Date: 2-16-89

Fuel	FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
NG	9.98E+05	0.81	1.37	17.76	62	46	0,1
#2	2.25E+06	0.94	1.18	18.20	58	432	2,3,4,5,6
#2	2.02E+06	1.05	1.31	19.38	67	983	7,8
#2	2.07E+06	1.02	1.27	19.30	65	809	9,10,11
#2	1.87E+06	1.13	1.42	20.26	74	1361	11,12
#2	1.82E+06	1.16	1.45	20.70	76	1293	12,13
#2	1.55E+06	1.36	1.70	22.09	81	778	14,15,16

(continued)

TABLE B-6. (continued)

Date: 2-21-89

Fuel	FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
NG	9.98E+05	1.06	1.71	17.36	69	417	0,1,2
NG	9.98E+05	0.80	1.45	17.11	70	544	2,3,4
#2	1.67E+06	1.26	1.57	20.52	81	888	5,6,7
#2	1.73E+06	1.22	1.52	20.22	78	1034	7,8,9
#2	1.79E+06	1.18	1.47	20.10	75	1230	9,10,11,12,13,14,15,16,17
#2	1.73E+06	1.22	1.52	20.23	77	1288	17,18

Date: 2-22-89

Fuel	FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
NG	9.98E+05	0.80	1.35	16.98	57	52	0,1
#2	1.76E+06	1.21	1.50	19.78	61	913	2,3,4,5,6
#2	1.66E+06	1.29	1.60	20.35	65	969	6,7
#2	1.76E+06	1.21	1.50	19.93	61	1065	7,8
#2	1.84E+06	1.16	1.44	19.69	58	1196	8,9
#2	1.81E+06	1.18	1.47	19.68	59	1292	9,10
#2	1.79E+06	1.20	1.49	20.09	61	1309	10,11
#2	1.84E+06	1.16	1.44	19.83	59	1351	11,12
#2	1.75E+06	1.22	1.51	20.38	62	1307	12,13,14
#2	1.80E+06	1.19	1.48	20.24	60	1345	14,15
#2	1.76E+06	1.21	1.50	20.53	62	1307	15,16,17

(continued)

TABLE B-6. (continued)

Date: 2-23-89

Fuel	FR (Btu/h)	SR1	SR2	Emissions (at 0% O2) CO2 (%)	CO (ppm)	NO (ppm)	Graph Points
NG	9.98E+05	0.81	1.36	17.58	62	78	0,1
#2	1.84E+06	1.15	1.43	19.80	11	870	2,3,4
#2	1.92E+06	1.10	1.37	19.42	9	1093	4,5,6,7
#2	1.81E+06	1.17	1.46	19.79	9	1269	8,9
#2	1.73E+06	1.22	1.52	19.91	12	1307	9,10
#2	1.76E+06	1.20	1.49	19.93	18	1380	11,12
#2	1.81E+06	1.17	1.46	19.96	27	1385	12,13,14,15,16

(continued)

TABLE B-7. FAILURE TESTING OF LIGHTWEIGHT REFRACTORY SPOOL—TEMPERATURES

Temperatures

	2-15-89			2-16-89			2-21-89			2-22-89			2-23-89		
Pt. #	Time (hrs	T1 (F)	T2 (F)	Time (hrs)	T1 (F)	T2 (F)	Time (hrs)	T1 (F)	T2 (F)	Time (hrs)	T1 (F)	T2 (F)	Time (hrs)	T1 (F)	T2 (F)
0	0.00	2560	2640	0.00	2340	2480	0.00	2550	2680	0.00	2470	2540	0.00	2430	2220
1	0.50	2560	2640	0.75	2340	2480	0.50	2550	2680	0.67	2470	2540	0.17	2430	2220
2	0.52	2680	2660	0.77	2800	2580	1.08	2380	2600	0.75	2220	2340	0.25	2820	2620
3	1.33	2500	2380	1.25	2910	2790	1.13	2360	2660	0.83	2600	2500	1.00	2975	2780
4	1.35	2380	2400	1.50	2950	2800	1.50	2360	2660	1.00	2800	2630	1.33	2988	2790
5	1.70	2440	2490	1.52	2990	2800	1.53	2200	2320	1.25	2882	2660	3.08	2970	2820
6	1.75	2380	2560	2.00	3000	2810	1.58	2680	2550	1.75	2910	2700	3.17	3003	2820
7	3.92	2510	2670	2.02	3000	2790	1.75	2671	2620	2.50	2859	2660	3.50	3014	2830
8	3.93	2580	2640	4.00	3040	2840	2.83	2878	2630	3.00	2925	2720	3.53	2992	2810
9	7.00	2600	2650	4.25	2500	2550	3.75	2930	2670	3.50	2985	2780	5.08	3009	2820
10	7.02	2240	2360	4.33	3004	2740	4.00	2970	2750	5.33	3021	2810	5.67	2956	2810
11	7.50	2920	2600	4.50	3019	2790	5.00	2976	2770	6.25	3008	2780	5.7	2989	2810
12	9.5	2980	2700	5.75	3112	2790	6.00	2989	2790	6.50	3020	2810	6.83	2975	2810
13				7.67	3127	2790	6.50	2996	2800	7.00	2977	2790	7.00	2995	2820
14				7.75	3000	2660	7.00	3000	2810	8.00	2992	2790	7.50	3010	2830
15				8.00	2975	2640	7.50	3002	2820	8.25	3012	2820	8.00	2993	2830
16				9.00	2980	2580	8.00	3005	2820	8.75	2986	2800	8.17	2996	2830
17							8.50	3008	2820	9.00	2967	2800			
18							9.50	2996	2800						

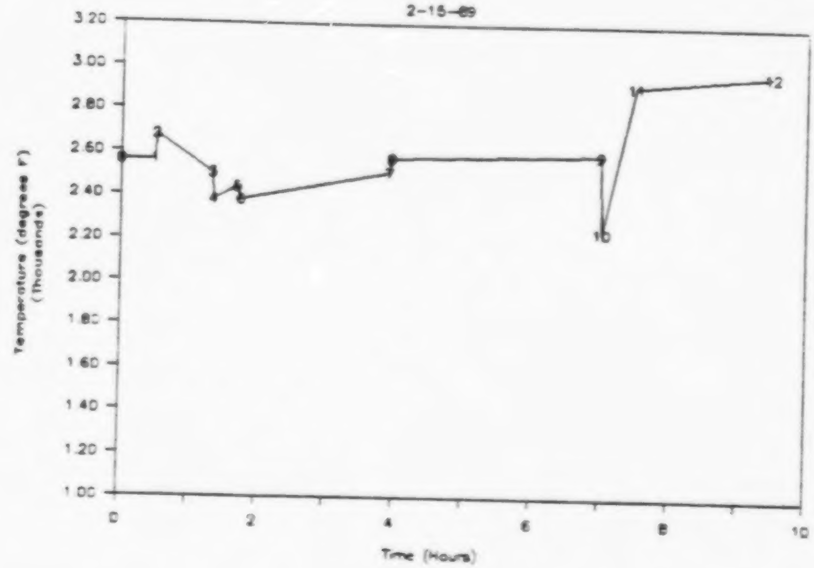


Figure B-13. Bore temperatures (T1)—2-15-89.

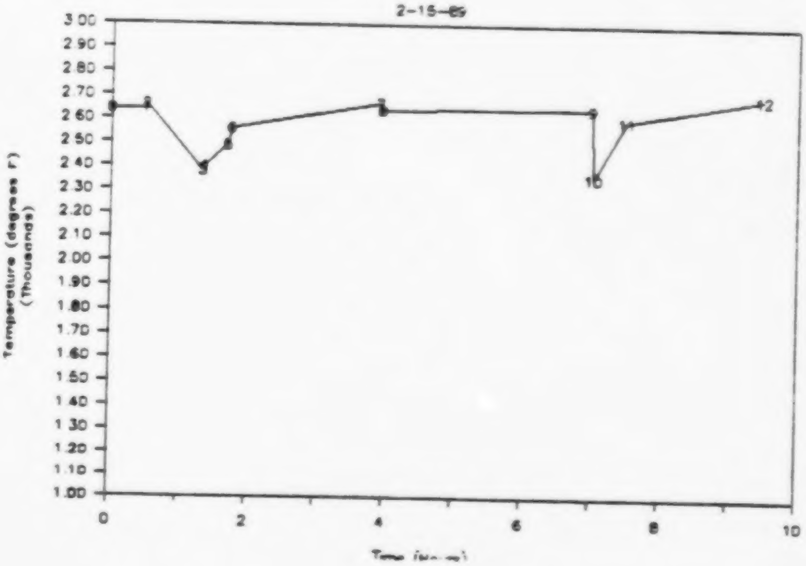


Figure B-14. Inner spool temperatures (T2)—2-15-89.

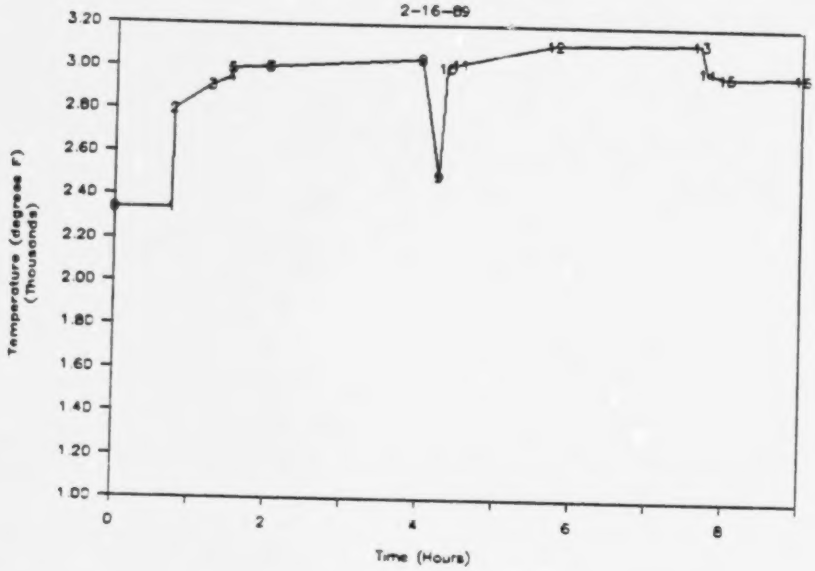


Figure B-15. Bore temperatures (T1)—2-16-89.

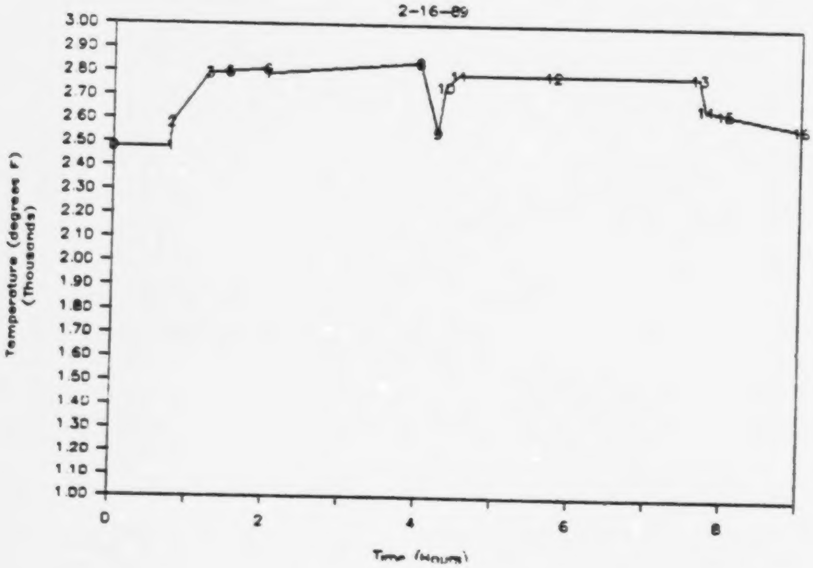


Figure B-16. Inner spool temperatures (T2)—2-16-89.

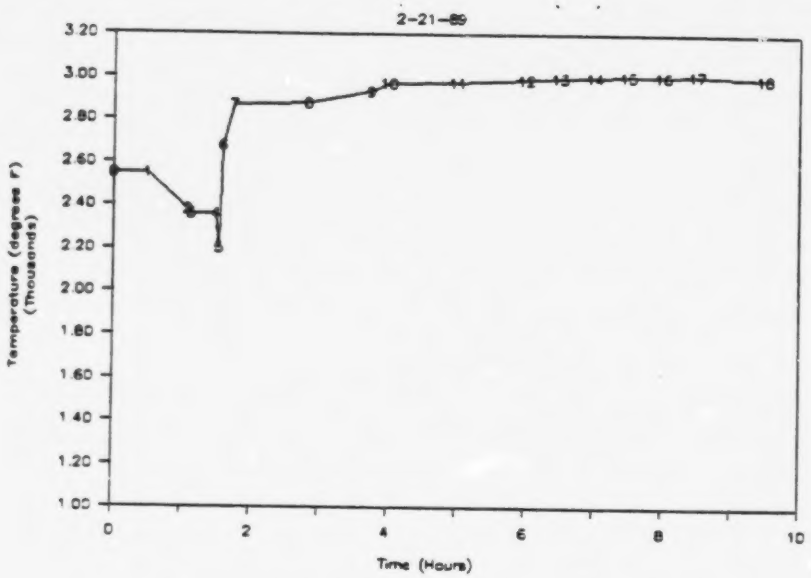


Figure B-17. Bore temperatures (T1)—2-21-89.

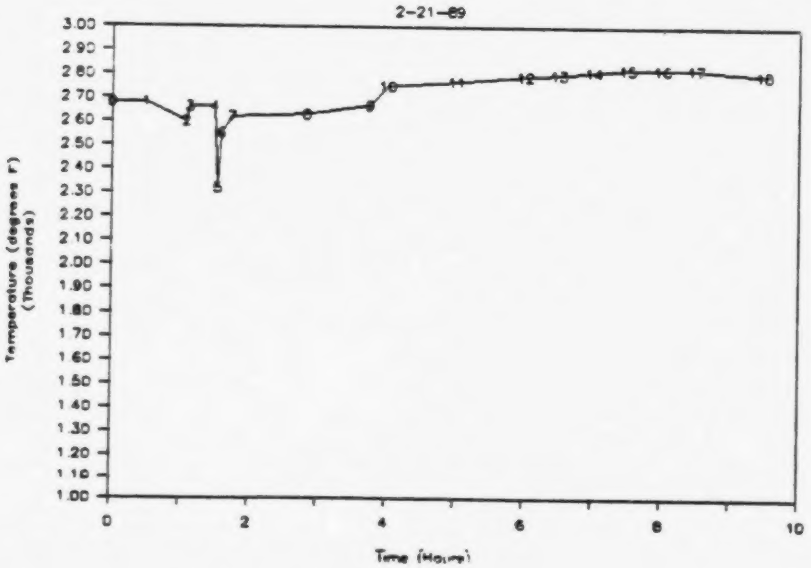


Figure B-18. Inner spool temperatures (T2)—2-21-89.

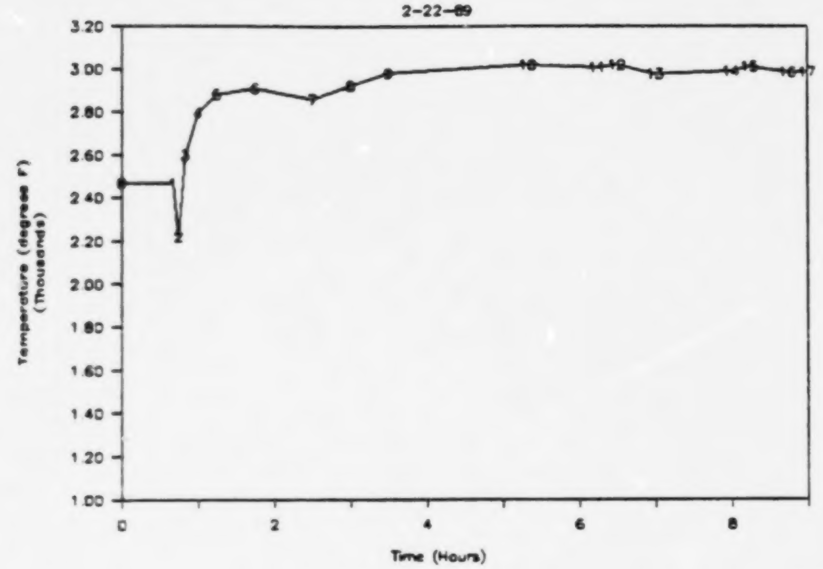


Figure B-19. Bore temperatures (T1)—2-22-89.

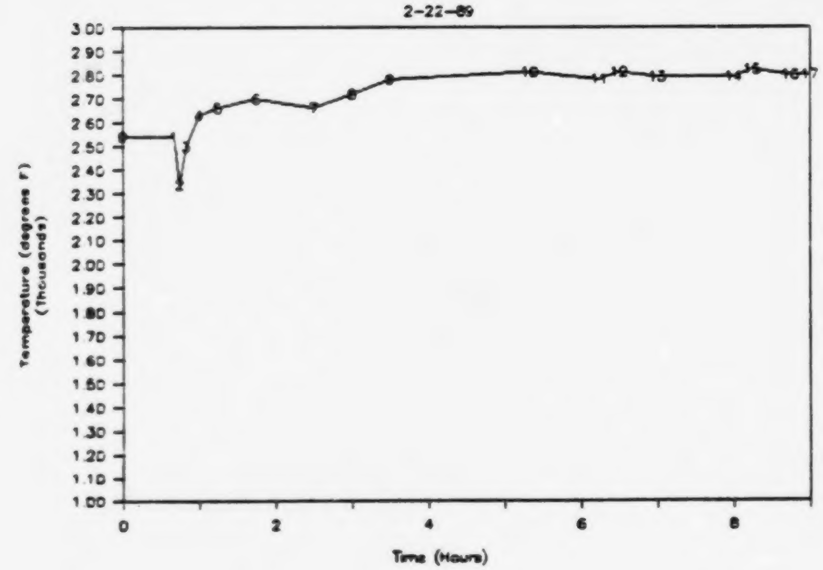


Figure B-20. Inner spool temperatures (T2)—2-22-89.

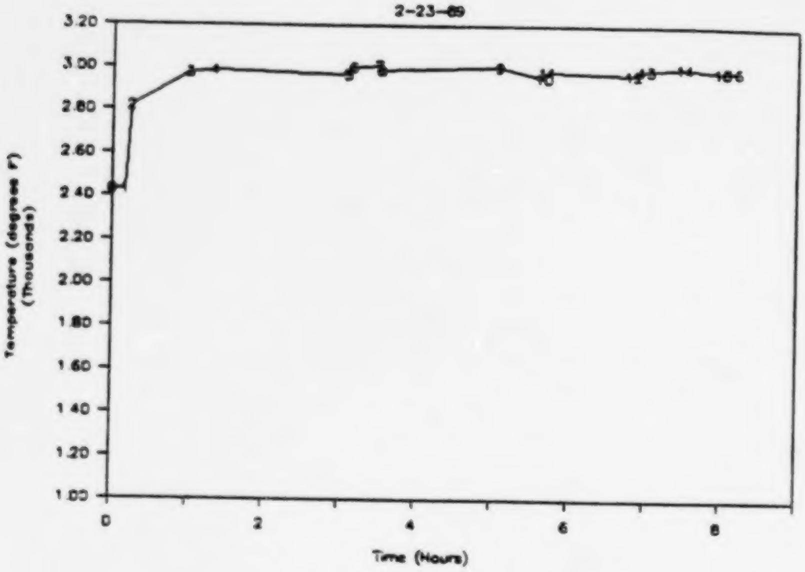


Figure B-21. Bore temperatures (T1)—2-23-89.

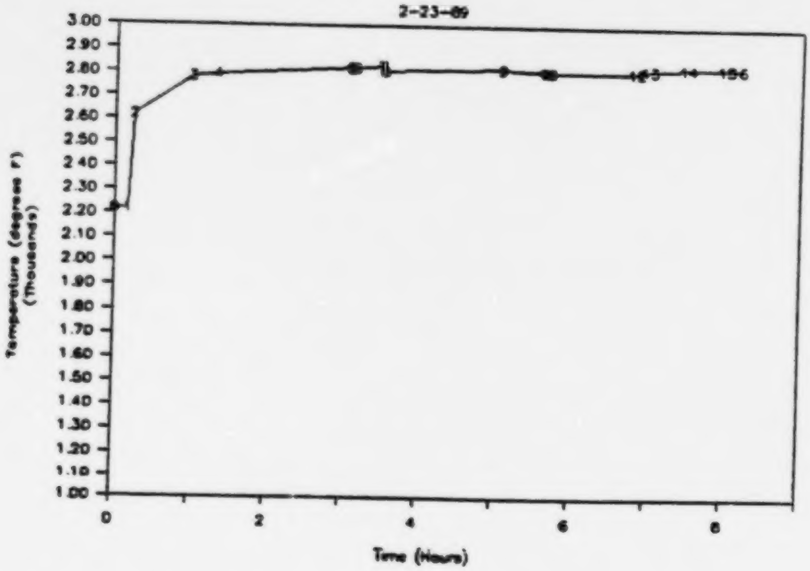
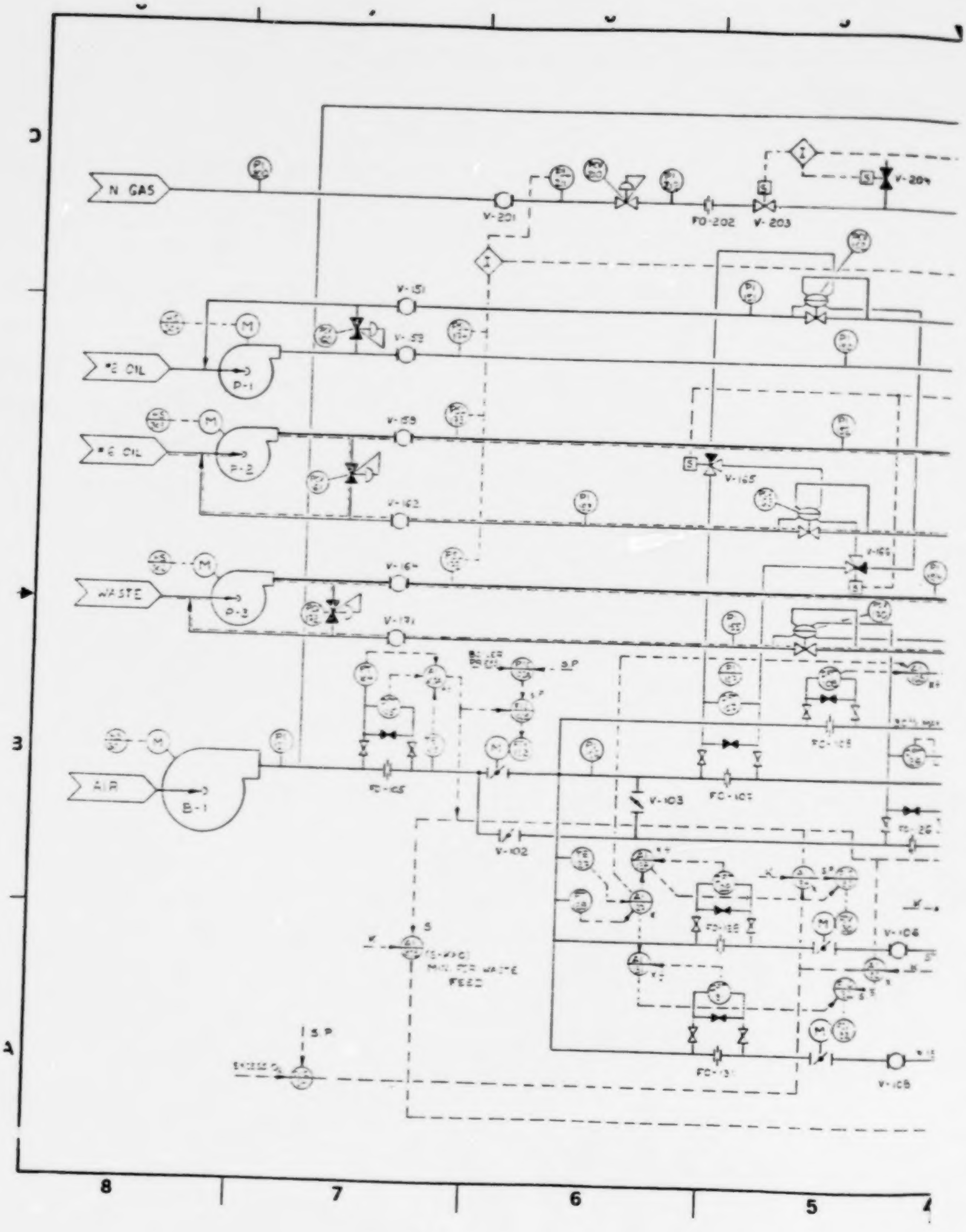
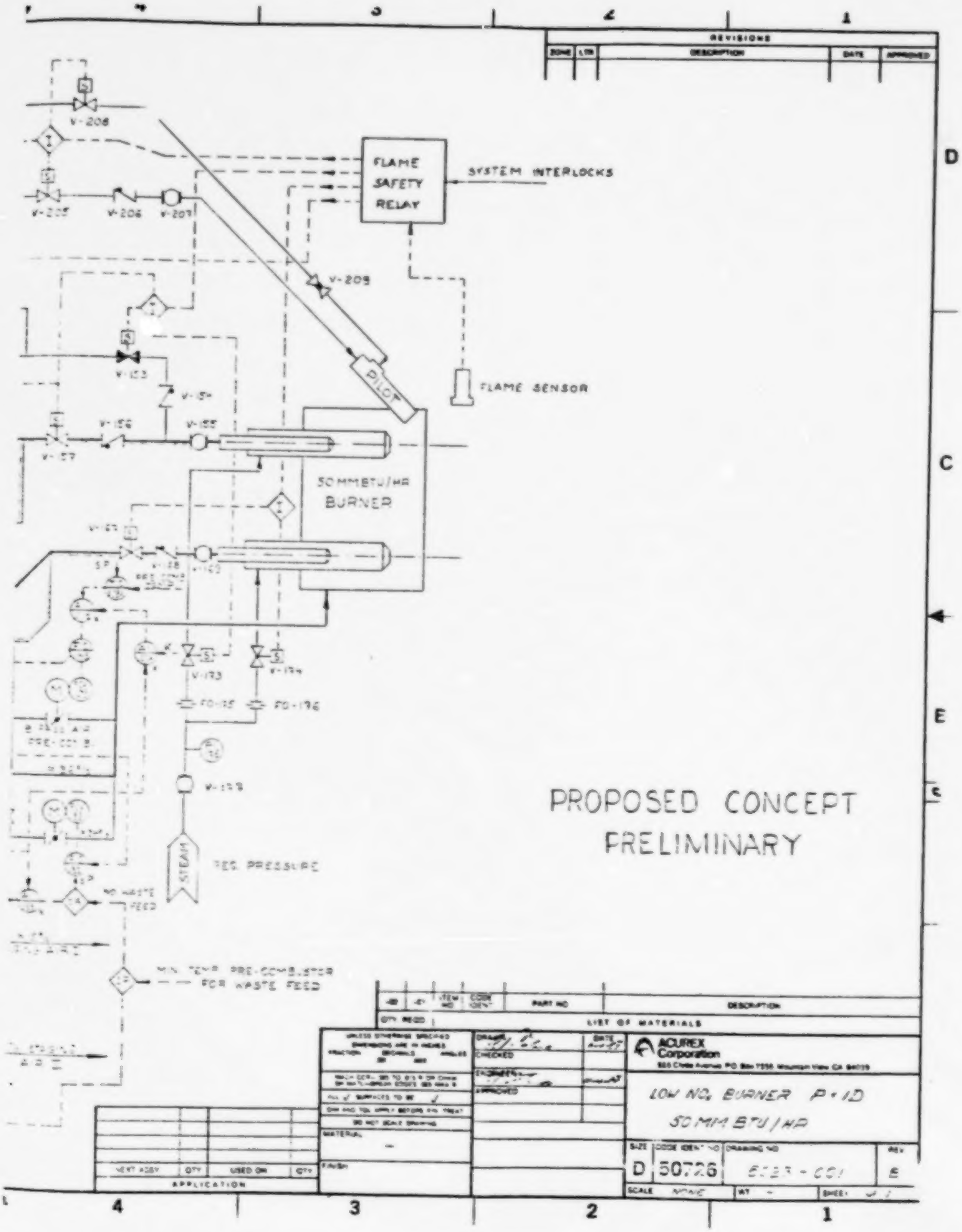


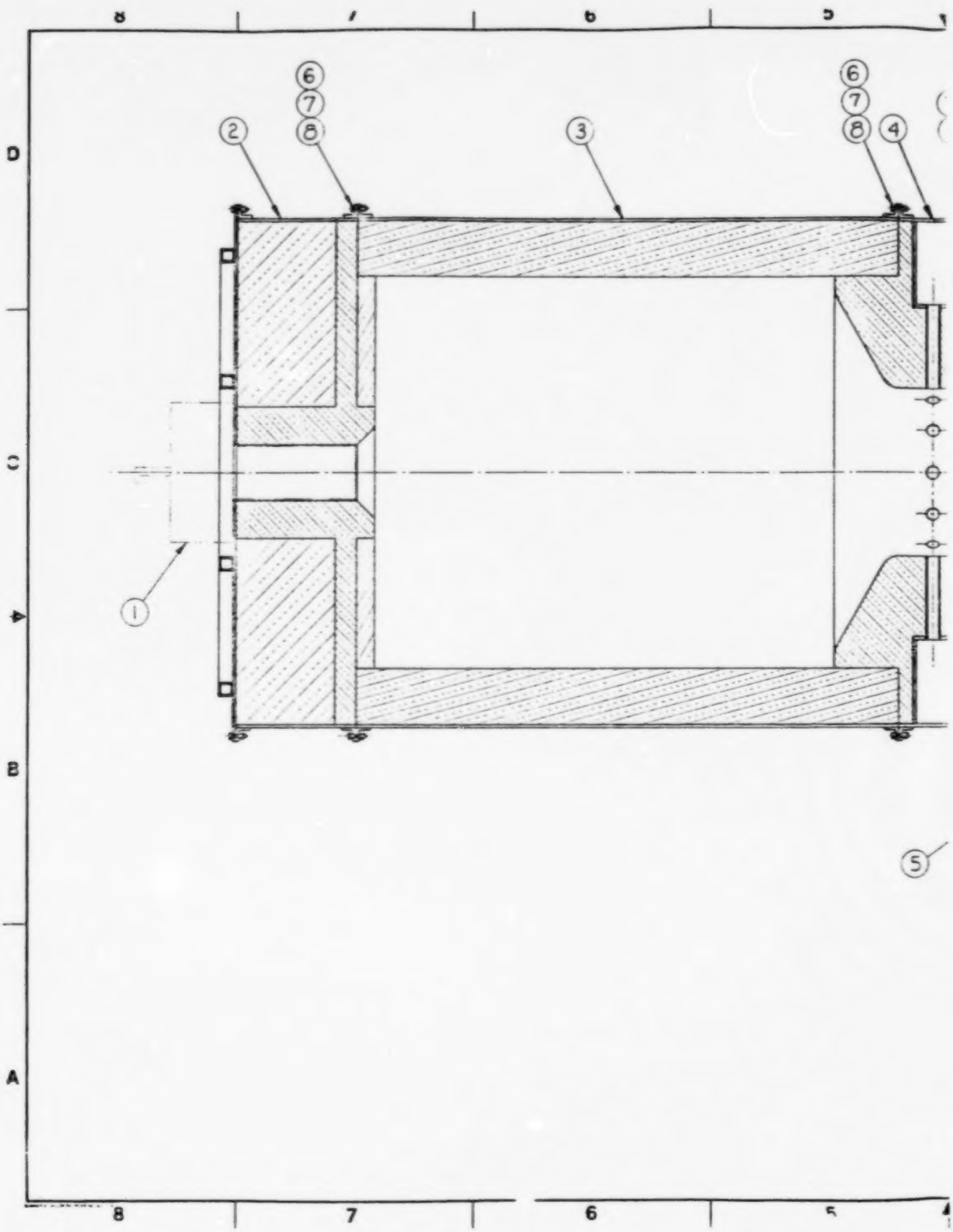
Figure B-22. Inner spool temperatures (T2)—2-23-89.

APPENDIX C

DESIGN DRAWINGS


D
C
B
A
N GAS
V-201
FO-202
V-203
V-204
V-151
V-153
#2 OIL
P-1
#6 OIL
P-2
V-159
V-165
V-162
V-166
WASTE
P-3
V-164
V-171
BOILER PRESS
S.P
AIR
B-1
FO-105
V-102
V-103
FO-107
FO-108
FO-126
FO-129
FO-131
V-104
V-105
MIN. FOR WASTE FEED
EXCESS O2
M
S
8
7
6
5
4


REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
V-208
V-205
V-206
V-207
FLAME
SAFETY
RELAY
SYSTEM INTERLOCKS
V-209
PILOT
FLAME SENSOR
V-123
V-154
V-156
V-155
V-157
50 MMBTU/HR
BURNER
V-160
V-173
V-174
FO-175
FO-176
V-179
STEAM
REG. PRESSURE
NO WASTE
FEED
MIN. TEMP. PRE-COMBUSTOR
FOR WASTE FEED
PROPOSED CONCEPT
PRELIMINARY
LIST OF MATERIALS
PART NO
DESCRIPTION
QTY REQD
ITEM NO
CODE IDENT
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
DO NOT SCALE DRAWING
MATERIAL
FINISH
NEXT ASSY
USED ON
QTY
APPLICATION
DRAWN
CHECKED
ENGINEER
APPROVED
DATE
ACUREX
Corporation
555 Clyde Avenue PO Box 7555 Mountain View CA 94039
LOW NOx BURNER P+ID
50 MM BTU/HR
SIZE
D
CODE IDENT NO
50726
DRAWING NO
5323 - 001
REV
E
SCALE NONE
WT -
SHEET
D
C
E
4
3
2
1


8
7
6
5
D
C
B
A
②
⑥
⑦
⑧
③
⑥
⑦
⑧
④
①
⑤
8
7
6
5

REVISIONS				
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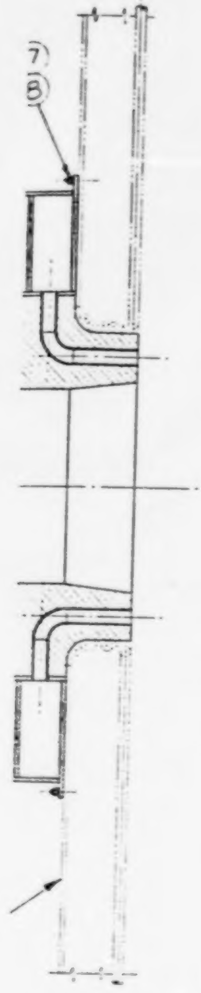


-01 50 MBTU/HR CHAMBER
-02 200 MBTU/HR CHAMBER

* NOTE: ITEM 3 MAY BE REPLACED BY OR EXTENDED BY CENTRAL SECTION "A" OR CENTRAL SECTION "B" OR BY BOTH. SEE DWG 8023-102 & 8023-103.

-02	-01	ITEM NO	CODE IDENT	PART NO	DESCRIPTION	
120	96	8			NUT, 5/8"-11UNC HEAVY DUTY	STL ZINC PL
120	96	7			WASHER, 5/8" NOM. SPLIT LOCK	
80	64	6			BOLT, 5/8"-11UNC x 1 1/4 LG MACH	STL ZINC PL
1	1	5			BOILER (REF)	
1	1	4		8023-105	BOILER END SECTION	
1	1	3		8023-104*	CENTRAL SECTION "C" *	
1	1	2		8023-101	BURNER END SECTION	
1	1	1			BURNER (REF)	

QTY REQD
LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
DO NOT SCALE DRAWING
MATERIAL
FINISH

DRAWN DJT
CHECKED
ENGINEER
APPROVED

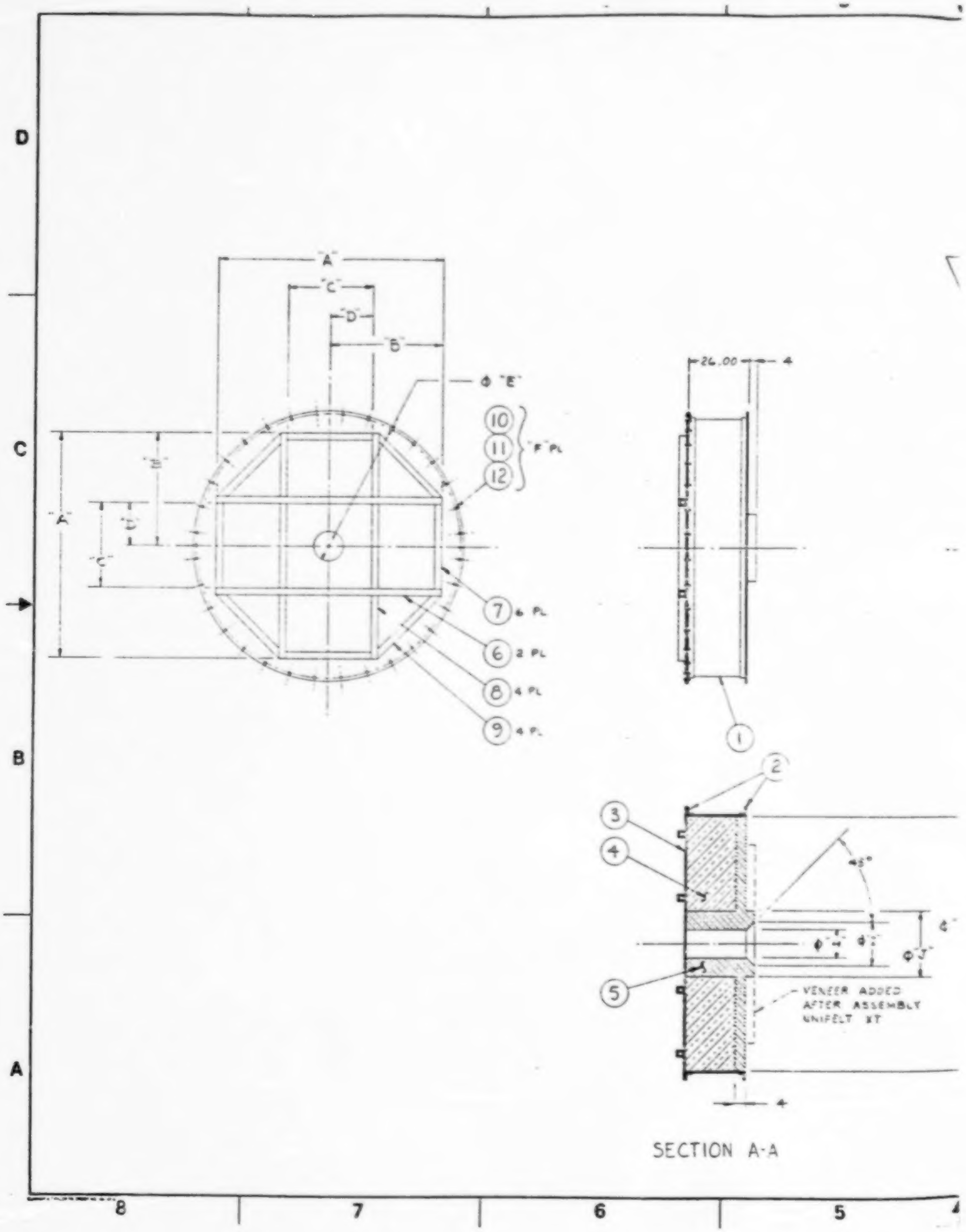
acurex corporation
MOUNTAIN VIEW, CA

COMBUSTION CHAMBER
TOP ASSEMBLY

SIZE	CODE IDENT NO	DRAWING NO	REV
D	50726	8023-100	A

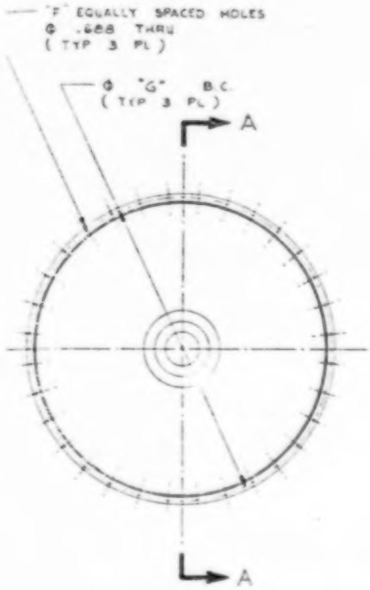
SCALE NONE

NEXT ASSY | QTY | USED ON | QTY
APPLICATION



D
C
B
A
8
7
6
5
4
"A"
"C"
"D"
"B"
Φ "E"
⑩
⑪
⑫
"F" PL
⑦ 6 PL
⑥ 2 PL
⑧ 4 PL
⑨ 4 PL
"A"
"B"
"D"
"C"
26.00
4
①
②
③
④
⑤
45°
"G"
Φ "H"
Φ "I"
Φ "J"
VENEER ADDED
AFTER ASSEMBLY
UNIFELT XT
4
SECTION A-A

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	ADDED -02 INFORMATION	3-2-89	DJT



DIM	-01	-02
A	96.00	118.00
B	48.00	59.00
C	36.00	45.00
D	18.00	22.50
E	12.06	17.06
F	32	40
G	112.00	136.00
H	12	17
I	20	25
J	28	33
K	108	132
L	38 3/16	47 1/8
M	27	33 1/2
N	36	45
O	96	118
P	114.75	138.75
Q	360.50	435.90
R	341.65	417.05
S	19	24
T	16	20
U	21	27
V	54	67
W	1089	1592
X	232	281
Y	942	1150

-02	-01	ITEM NO	CODE IDENT	PART NO	DESCRIPTION	WT
40	32	12			5/8 NOM SPLIT LOCK WASHER 2x PL	
40	32	11			5/8-11UNC HEX NUT, HEAVY 2x PL	
40	32	10			5/8-11UNC HEX HD MACH BOLT x 1 3/4 LG 2x PL	
4	4	9			3 x 3 x 3/16 WALL x "L" LG SQR STR TUBE ASTM A500 STL	"S"
4	4	8			3 x 3 x 3/16 WALL x "M" LG SQR STR TUBE ASTM A500 STL	"T"
6	6	7			3 x 3 x 3/16 WALL x "N" LG SQR STR TUBE ASTM A500 STL	"U"
2	2	6			3 x 3 x 3/16 WALL x "O" LG SQR STR TUBE ASTM A500 STL	"V"
AS REQ'D	AS REQ'D	5			REFRACTORY, PLASCAST 85	
AS REQ'D	AS REQ'D	4			REFRACTORY, H.W. LIGHTWEIGHT CASTABLE 26	
1	1	3			PL 5/8 x "P" O.D. STR. QUAL. H.R. ASTM A36 STL	"W"
2	2	2			L 3 x 3 x 3/8 x "Q" ASTM A36 STL	"X"
1	1	1			PL 3/8 x 26 x "R" STR. QUAL. H.R. ASTM A36 STL	"Y"
QTY REQD			LIST OF MATERIALS			

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
FRACTION ± 1/8 DECIMALS .XX ± .06 .XXX ± .010 ANGLES ± 0° 30'
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
DO NOT SCALE DRAWING
MATERIAL SEE L/M
FINISH

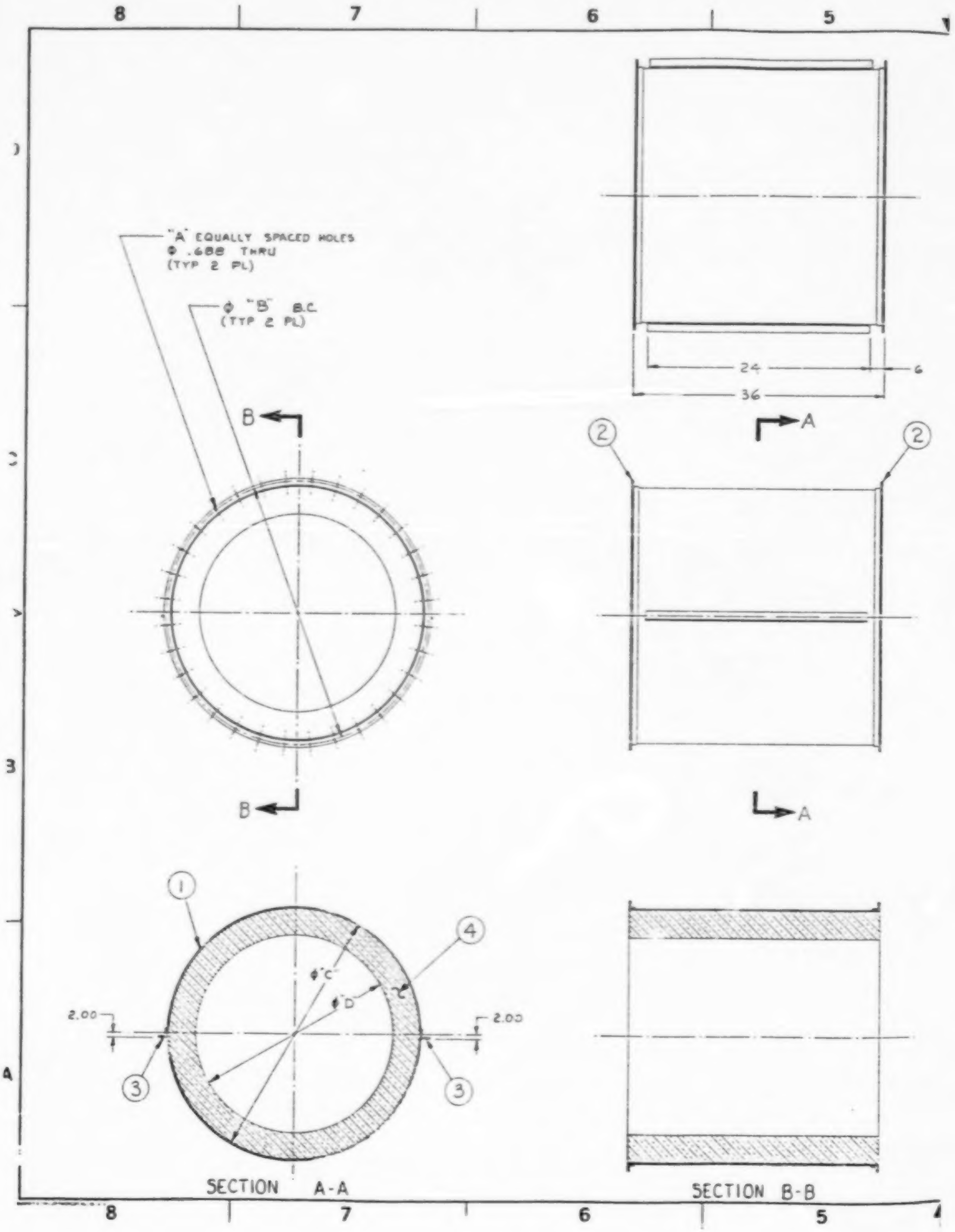
DRAWN DJT DATE 11-5-87
CHECKED
ENGINEER
APPROVED

acurex corporation MOUNTAIN VIEW, CA

COMBUSTION CHAMBER
BURNER END SECTION

SIZE D
CODE IDENT NO 50726
DRAWING NO 8023-101
REV A
SCALE NONE
WT
SHEET 1 OF 1

NEXT ASSY	QTY	USED ON	QTY
		8023-100	
APPLICATION			



8
7
6
5
"A" EQUALLY SPACED HOLES
Ø .688 THRU
(TYP 2 PL)
Ø "B" B.C.
(TYP 2 PL)
24
6
36
B
B
A
A
2
2
1
4
Ø "C"
Ø "D"
2.00
2.00
3
3
SECTION A-A
SECTION B-B
8
7
6
5

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
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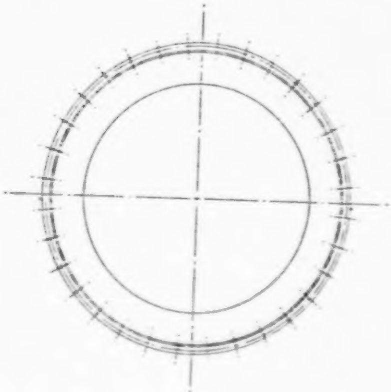
DIM	-01	-02
A	32	40
B	112.00	136.00
C	108	132
D	84	108
E	360.50	435.90
F	341.65	417.05
G	837	1047
H	232	281
I	1305	1593



AS REQD	AS REQD	4			REFRACTORY, PYROBLOCK PLUS		G
2	2	3			L 4 x 4 x ½ x 24.00	ASTM A36 STL	24
2	2	2			L 3 x 3 x ⅜ x "E"	ASTM A36 STL	H
1	1	1			℞ ⅜ x 36 x "F" STR QUAL H.R.	ASTM A36 STL	I
-02	-01	ITEM NO	CODE IDENT	PART NO	DESCRIPTION		WT
QTY REQD							

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTION DECIMALS ANGLES
± ⅛ .XX ±.06 .XXX ±.010
[illegible]
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE [illegible] TREAT
DO NOT SCALE DRAWING
MATERIAL SEE L/M
FINISH

DRAWN	DJT	DATE 11-4-87
CHECKED		
ENGINEER	DJ Tolen	11-[illegible]
APPROVED		

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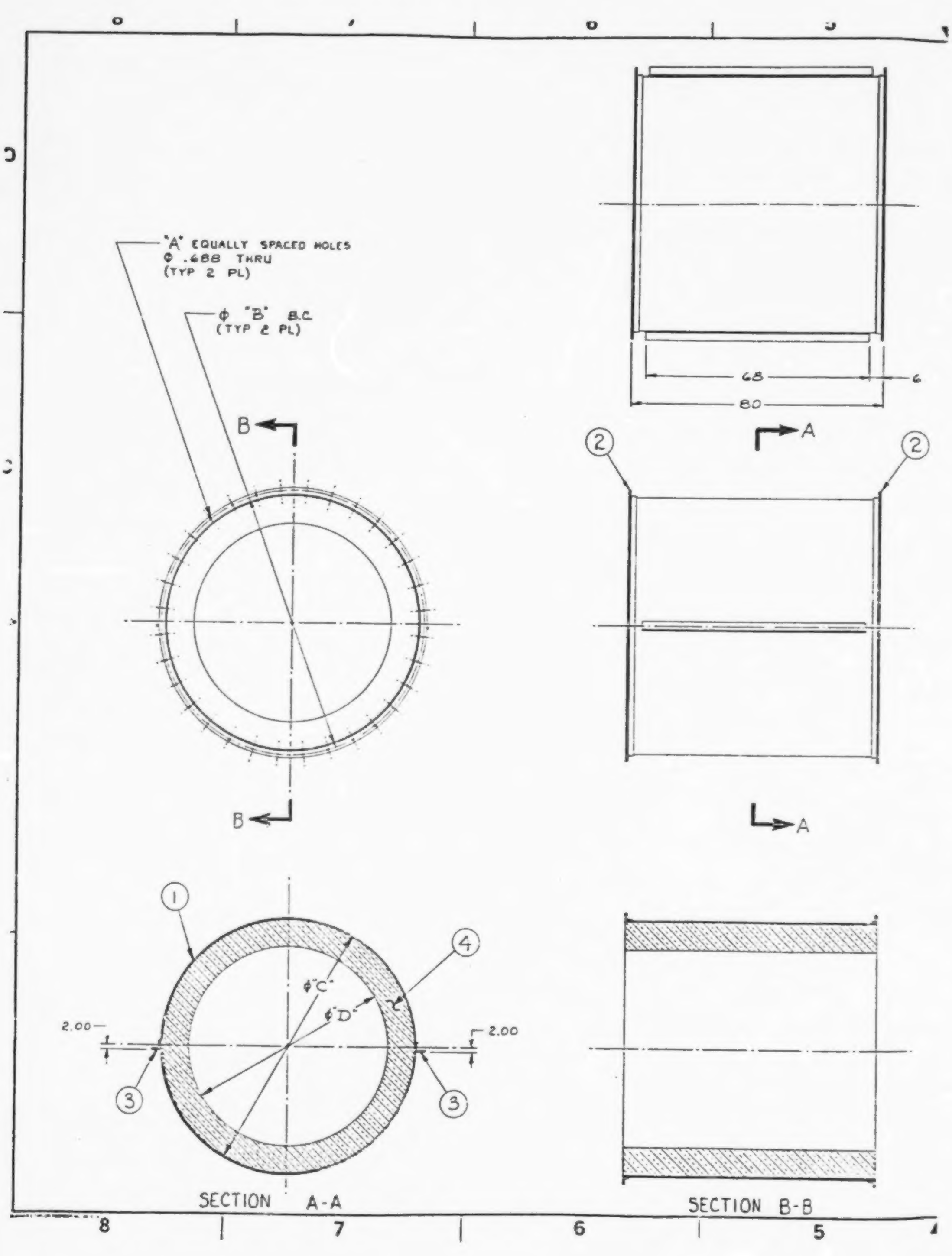
MOUNTAIN VIEW, CA

COMBUSTION CHAMBER
CENTRAL SECTION "A"

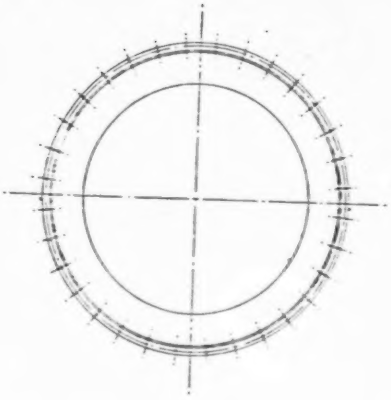
SIZE	CODE IDENT NO	DRAWING NO	REV
D	50726	80[illegible]-102	A
SCALE NONE		WT	SHE[illegible] 1 OF 1

NEXT ASSY	QTY	USED ON	QTY
		8023-100	

APPLICATION


"A" EQUALLY SPACED HOLES
Φ .688 THRU
(TYP 2 PL)
Φ "B" B.C.
(TYP 2 PL)
68
6
80
B
B
A
A
2
2
1
4
3
3
ΦC
ΦD
2.00
2.00
SECTION A-A
SECTION B-B
8
7
6
5

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	ADDED -02 INFORMATION	3-2-89	17



DIM	-01	-02
A	32	40
B	112.00	136.00
C	108	132
D	54	103
E	360.50	435.90
F	341.65	417.05
G	1858	2327
H	232	281
I	2558	3540

LIST OF MATERIALS

QTY REQD -02	QTY REQD -01	ITEM NO	CODE IDENT	PART NO	DESCRIPTION		WT
AS REQD	AS REQD	4			REFRACTORY, PYROBLOCK PLUS		G
2	2	3			L 4×4×½×68.00	ASTM A36 STL	73
2	2	2			L 3×3×⅜×"E"	ASTM A36 STL	H
	1	1			PL ⅜×80×"F" STR QUAL. H.R.	ASTM A36 STL	I

NEXT ASSY	QTY	USED ON	QTY
		8023-100	

APPLICATION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

FRACTION	DECIMALS .XX	DECIMALS .XXX	ANGLES
± ⅛	± .06	± .010	

MACH COR— .005 TO .015 R OR CHAM SH MATL—BREAK EDGES .005 MAX R

ALL ✓ SURFACES TO BE ✓

DIM AND TOL APPLY BEFORE FIN TREAT

DO NOT SCALE DRAWING

MATERIAL SEE L/M

FINISH

		DATE
DRAWN	DJT	11-4-87
CHECKED		
ENGINEER	Tolno	
APPROVED		

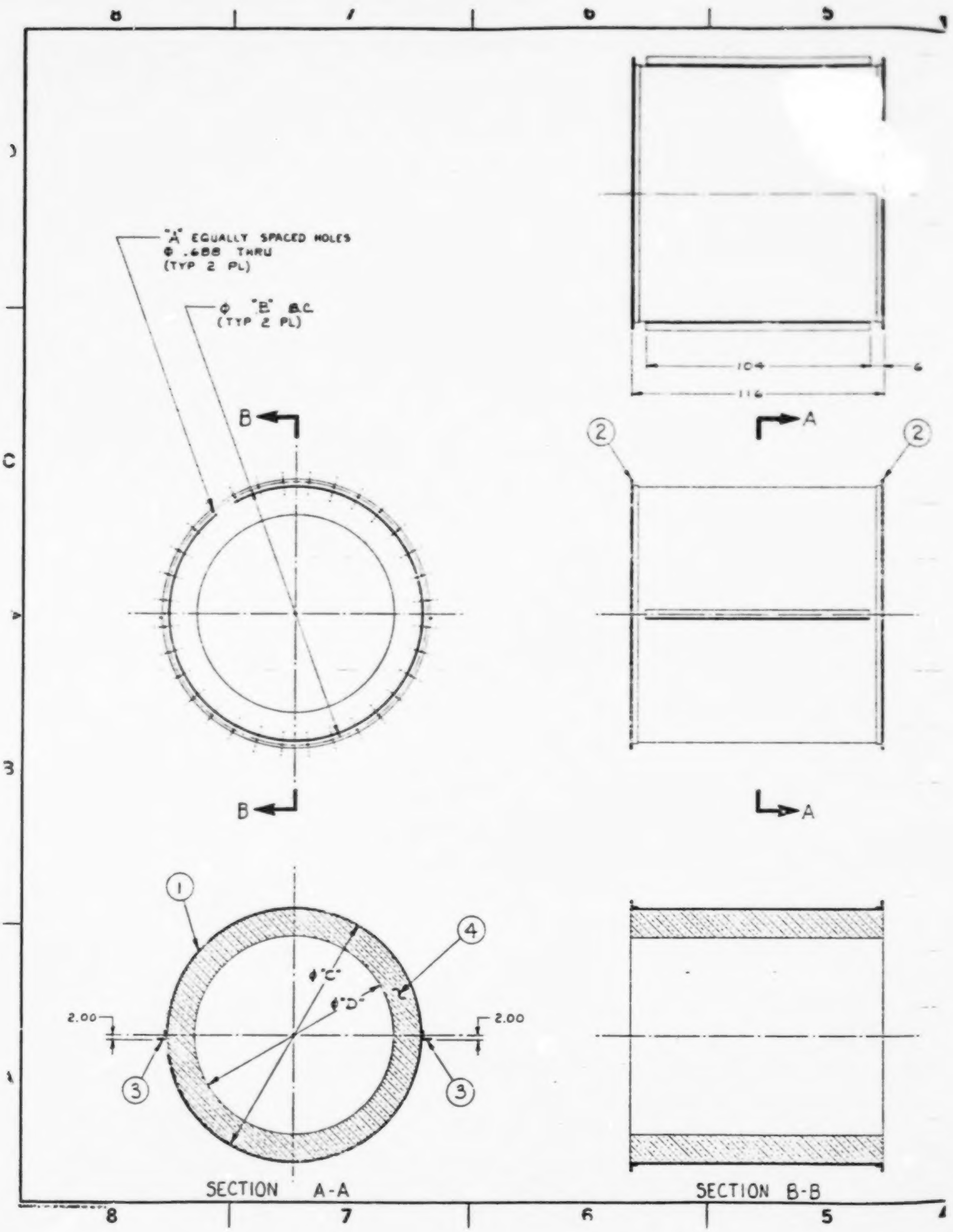
acurex corporation

MOUNTAIN VIEW CA

COMBUSTION CHAMBER
CENTRAL SECTION "B"

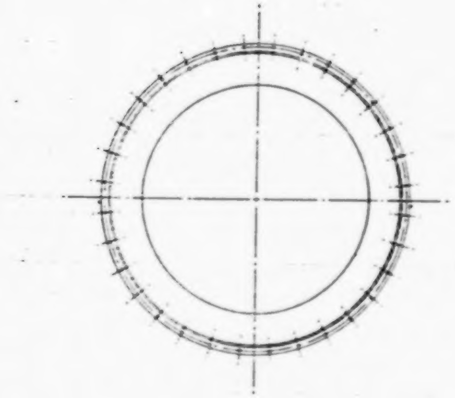
SIZE	CODE IDENT NO	DRAWING NO	REV
D	50726	8023-103	A

SCALE NONE WT SH OF 1


"A" EQUALLY SPACED HOLES
Φ .688 THRU
(TYP 2 PL)
Φ "B" B.C.
(TYP 2 PL)
104
6
116
B
B
A
A
②
②
①
④
③
③
Φ"C"
Φ"D"
2.00
2.00
SECTION A-A
SECTION B-B
8
7
6
5
D
C
B

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	ADDED -02 INFORMATION	2-2-89	[illegible]

DIM	-01	-02
A	32	40
B	112.00	136.70
C	108	132
D	84	106
E	340.50	435.90
F	341.65	417.95
G	2693	3275
H	232	291
I	4202	6093



-02	-01	ITEM NO	CODE IDENT	PART NO	DESCRIPTION		WT
AS REQD	AS REQD	4			REFRACTORY, PYROBLOCK PLUS		"G"
2	2	3			L 4 x 4 x ½ x 104.00	ASTM A36 STL	111
2	2	2			L 3 x 3 x ⅜ x "E"	ASTM A36 STL	"H"
1	1	1			R ⅜ x 116 x "F" STR QUAL H.R.	ASTM A36 STL	"I"

QTY REQD — LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FRACTION ± 1/16 DECIMALS .XX ±.06 .XXX ±.010 ANGLES
ALL ✓ SURFACES TO BE ✓
DIM AND TOL APPLY BEFORE FIN TREAT
DO NOT SCALE DRAWING
MATERIAL SEE L/M
FINISH

DRAWN DJT DATE 11-4-87
CHECKED
ENGINEER
APPROVED

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MOUNTAIN VIEW, CA

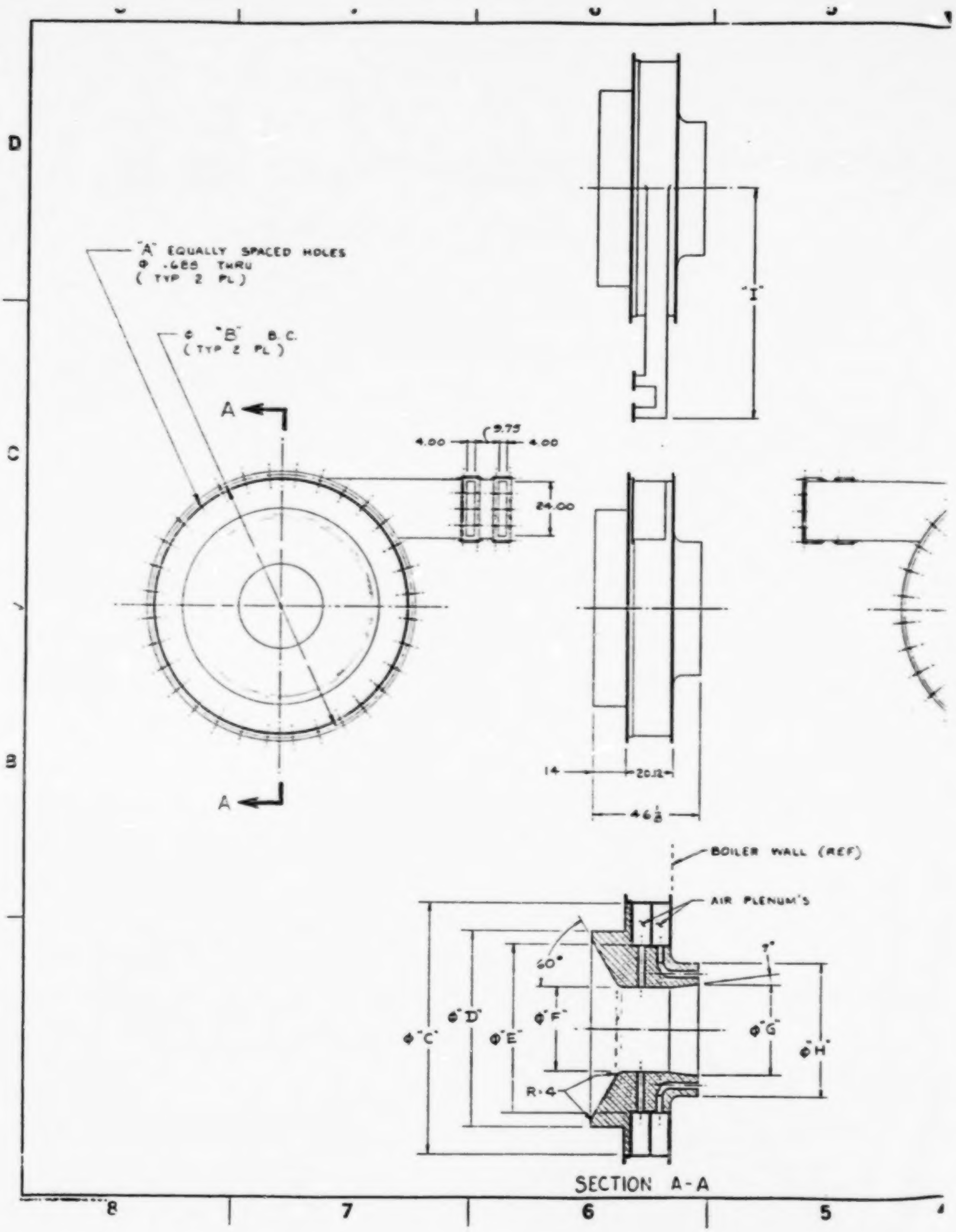
COMBUSTION CHAMBER
CENTRAL SECTION "C"

SIZE	CODE IDENT NO	DRAWING NO	REV
D	50726	8023-104	A

SCALE NONE WT - SHEET 1 OF 1

NEXT ASSY	QTY	USED ON	QTY
		8023-100	

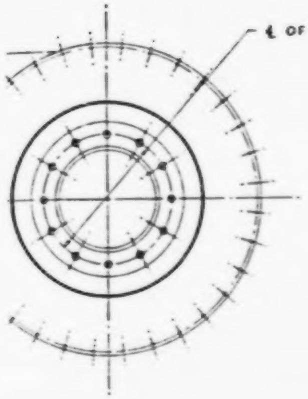
APPLICATION


"A" EQUALLY SPACED HOLES
Φ .688 THRU
(TYP 2 PL)
Φ "B" B.C.
(TYP 2 PL)
A
A
4.00
9.75
4.00
24.00
"I"
14
20.12
46 1/8
BOILER WALL (REF)
AIR PLENUM'S
60°
7°
Φ"C"
Φ"D"
Φ"E"
Φ"F"
Φ"G"
Φ"H"
R.4
SECTION A-A
D
C
B
8
7
6
5

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	B	ADDED -02 INFORMATION	3-2-89	DJT

NOTES:

1. MATERIALS:
   3/8" THK STL PL, STRUCTURAL QUALITY, ASTM A36
   L 3" x 3" x 3/8", ASTM A36 STL
   3" O.D. TUBE x .065 WALL D.O.M. CARBON STL, ASTM A513
   ELBOW, LONG RADIUS, 3" O.D. TUBE, .065 WALL
   REFRACTORY, PLASCAST 85



DIM	-01	-02
A	32	40
B	112.00	136.00
C	108	132
D	84	108
E	72	96
F	36	60
G	39	63
H	57	81
I	96.00	104.00
J	48.00	72.00

-02	-01	ITEM NO	CODE IDENT	PART NO	DESCRIPTION
QTY REQD					

LIST OF MATERIALS

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

DO NOT SCALE DRAWING

MATERIAL

FINISH

		8023-100	
NEXT ASSY	QTY	USED ON	QTY

APPLICATION

DRAWN DJT DATE 11-4-87

CHECKED

ENGINEER

APPROVED

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solar
corporation
MOUNTAIN VIEW CA

COMBUSTION CHAMBER BOILER END SECTION

SIZE D
CODE IDENT NO 50726
DRAWING NO 8023-105
REV B
SCALE NONE
WT
SHEET 1 OF 1